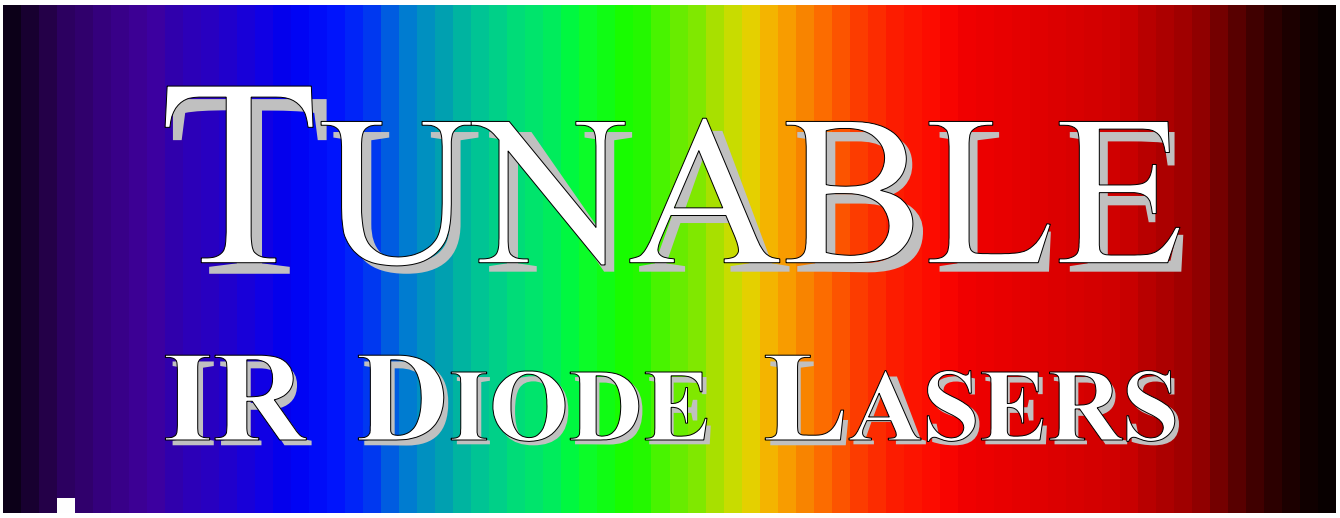
Boston Electronics Corporation
91 Boylston Street, Brookline, Massachusetts 02445 USA
(800)347-5445 or (617)566-3821 fax (617)731-0935
www.boselec.com boselec@boselec.com

Room Temperature



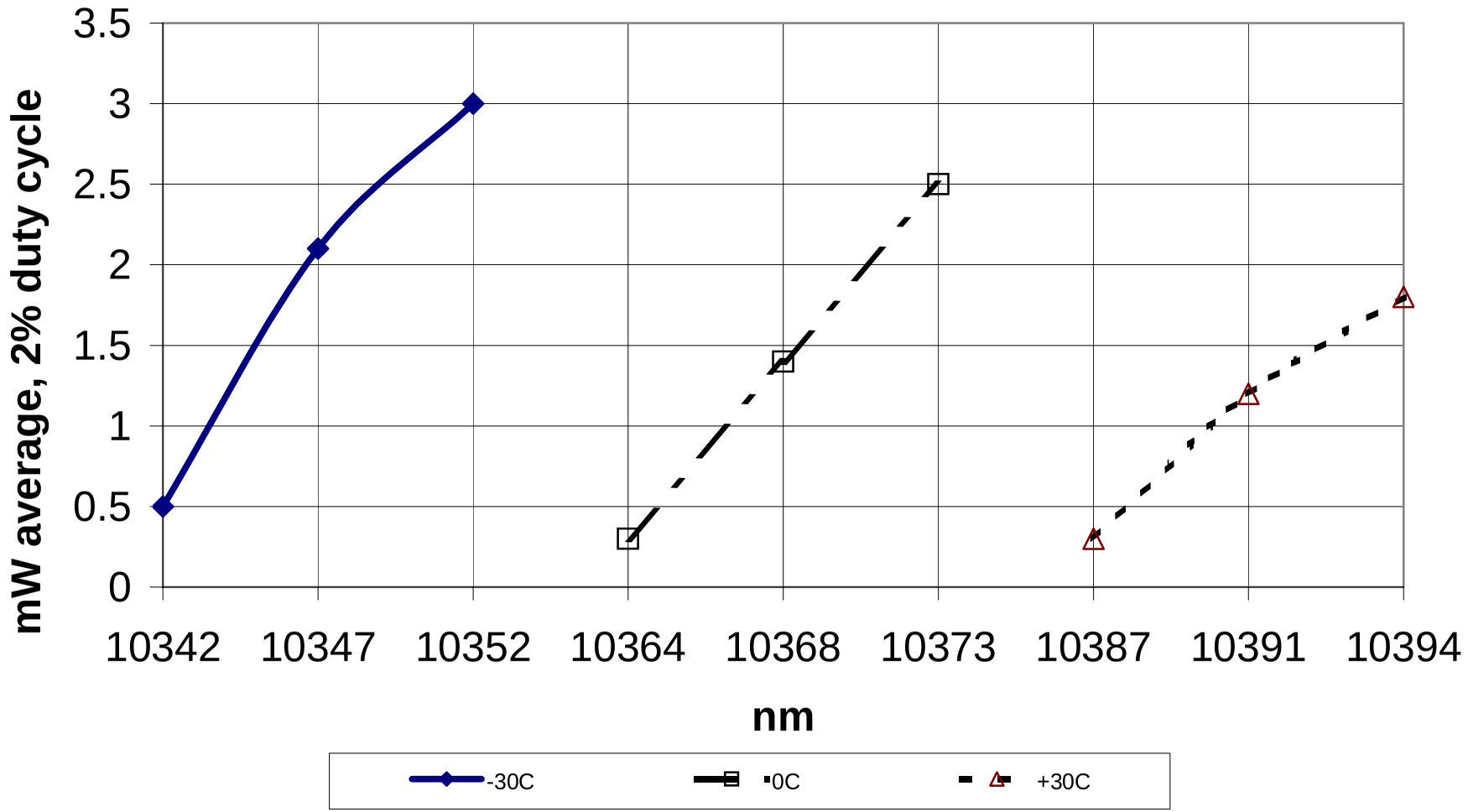
from

Alpes Lasers

Readily available:
Single Mode many devices between 4.3 and 10.4 μm
Multimode 5.0 to 6.2 and 8.5 to 10.6 μm

Built to order:
3.5 to >90 μm

Alpes #sb9 at different temps with different drive voltages



Boston Electronics
(800)347-5445 or qcl@boselec.com

High power and single frequency quantum cascade lasers for chemical sensing

Stéphane Blaser

final version: http://www.alpeslasers.ch/Conference-papers/QCLworkshop03.pdf

Collaborators

Alpes Lasers

Yargo Bonetti
Lubos Hvozdara
Antoine Muller
Guillaume Vandeputte
Hege Andersen

This work was done in collaboration with the University of Neuchâtel

Marcella Giovannini
Nicolas Hoyler
Mattias Beck
Jérome Faist

Outline

- Company profile
- Introduction - state of the art
  - High power Fabry-Pérot devices
- Applications
- Distributed-feedback lasers
  - High power pulsed DFB devices
  - >77K operating continuous-wave DFB devices
- Reliability
- Production

Company profile

- Founded August 1998 as a spin-off company from the University of Neuchâtel
  - incorporated as a SA under swiss law with a capital of 100 kCHF)
- Founders
  - Jérôme Faist
  - Antoine Muller
  - Mattias Beck
- Employees (September 2003)
  - 8 persons (6 full-time)

Installed at Maximilien-de-Meuron 1-3, 2000 Neuchâtel since April 2002

Company profile

- > 30 man-years experience
- 7 patents on QCL technologies

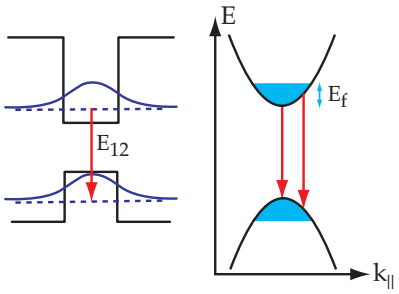
- > 150 devices sold
- > 50 customers

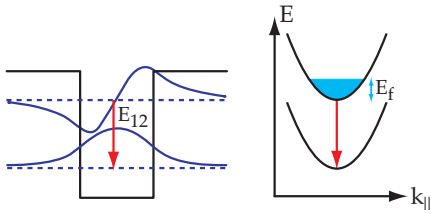
- turnover 2003: > 1.3 MCHF
- average growth rate: 100% / year

Alpes Lasers

Quantum cascade lasers

Interband vs intersubband



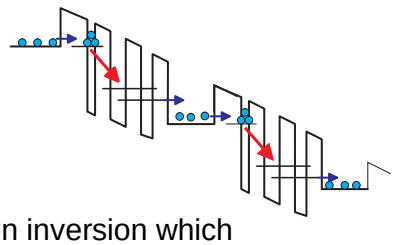


- **Interband transition**
  - bipolar
  - photon energy limited by bandgap E_g of material
  - Telecom, CD, DVD,…

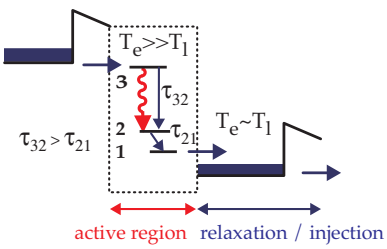
- **Intersubband transition**
  - unipolar, narrow gain
  - photon energy depends on layer thickness and can be tailored

Quantum cascade lasers

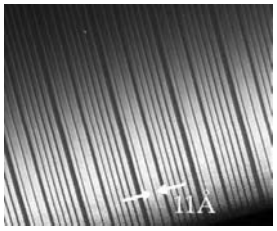
- **Cascade**
  - each e- emits N photons



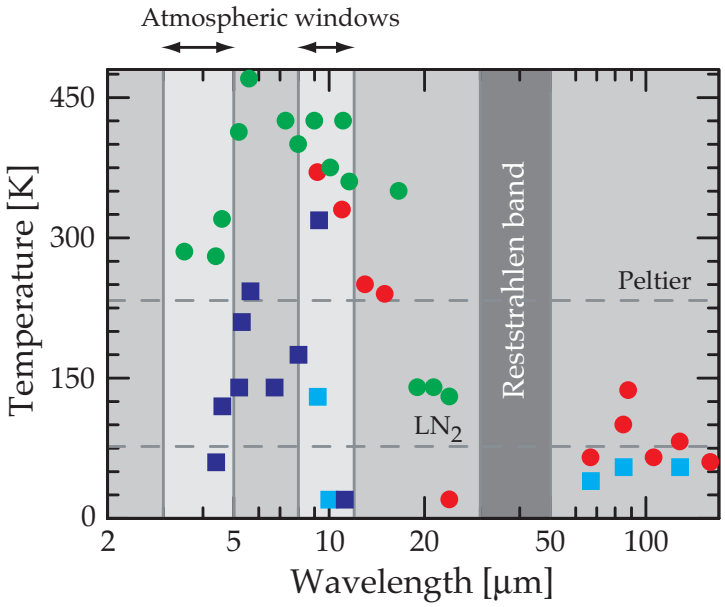
- **Active region / injector**
  - active region ➞ population inversion which must be engineered
  - injector ➞ avoid fields domains and cools down the electrons



- **MBE**
  - growth of thin layers
  - sharp interfaces



State of the art: QCL performances



CW, pulsed } InP

CW, pulsed } GaAs

- Good Mid-IR coverage
- Terahertz promising

Data:

MIR	FIR
Uni Neuchâtel	NEST Pisa
Alpes Lasers	MIT
Bell Labs	Uni Neuchâtel
Thales	
TU Vienna	
Northwestern Uni	
W. Schottky/TU Munich	

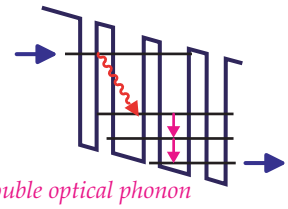
Designs

Double-phonon resonance:

(patent n° wo 02/23686A1)

- 4QW active region with 3 coupled lower state
- lower states separated by one phonon energy each
- keeps good injection efficiency of the 3QW design

Hofstetter *et al*. APL **78**, 396 (2001).



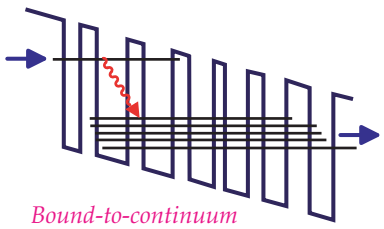
Double optical phonon resonance

Bound-to-continuum:

(patent n° wo 02/019485A1)

- transition from a bound state to a miniband
- combines injection and extraction efficiency
- broad gain curve -> good long-wavelength and high temperature operation

J. Faist *et al.* APL **78**, 147 (2001).



Bound-to-continuum

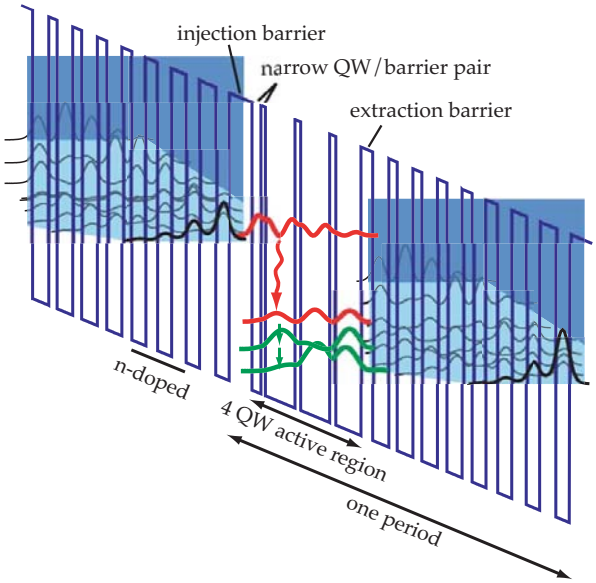
Two-phonon structure at 8 μm

Based on two-phonon resonances design

InGaAs/InAlAs-based heterostructure with ΔE_c = 0.52eV

Grown by MBE on InP substrate

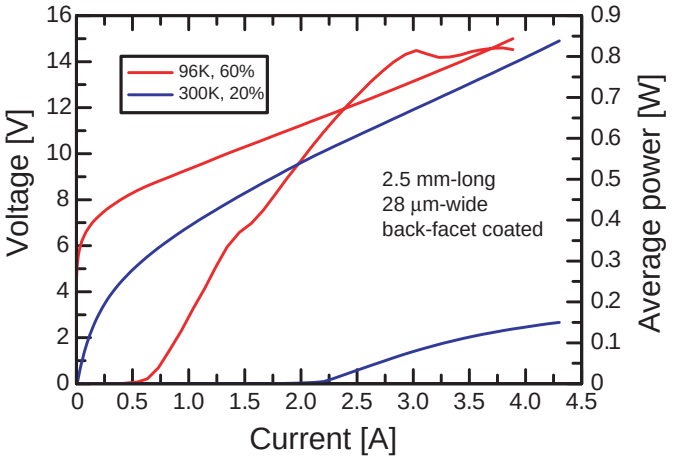
35 periods



41, 16, **8**, 53, **10**, 52, **11**, 45, **21**, 29, **15**, 28, **16**, 28, **17**, 27, **18**, 25, **21**, 25, **26**, 24, **29**, 24

High average power FP QCL

RT-HP-FP-150-1266



Characteristics

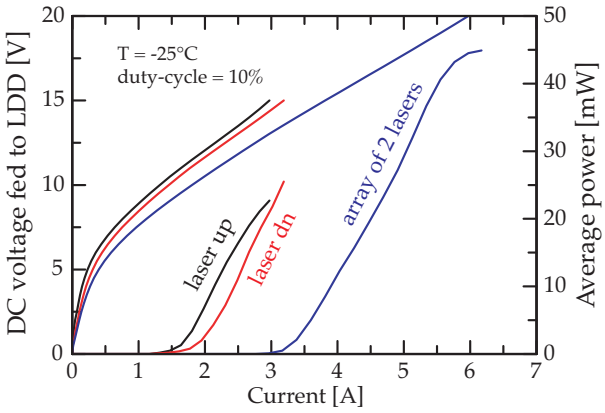
λ = 7.9 μm

@300K: Average power:
P = 150 mW
threshold current:
I_{th} = 2.1A (j_{th}=3.0 kA/cm^2)

@96K : P = 0.82 W (60% dc)
I_{th} = 0.51A (j_{th}=0.75 kA/cm^2)
CW: P = 300mW
(j_{th} = 0.78 kA/cm^2)

Array of lasers

DUAL-RT-HP-FP-40-1266



Characteristics

both lasers: 1.5 mm-long, 28 µm-wide
$\lambda \approx 7.9$ µm
T = -25°C, duty-cyle = 10%

laser	Average power	I_{th} [A]	j_{th} [kA/cm ^{2}]
up	25.4 mW	1.8	4.29
dn	22.6 mW	1.6	3.81
array	44.9 mW	3.4	4.05

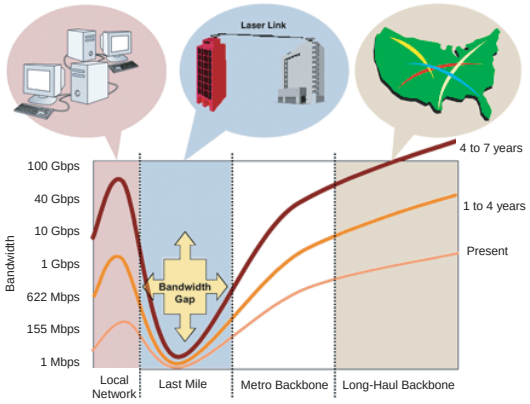
- Total power ≈ 90% (P_1+P_2)
- Total threshold current ≈ I_1+I_2

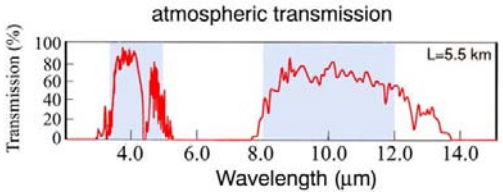
Alpes Lasers

Applications

Applications: telecom

- Telecommunications
  - Free-space optical data transmission for the last mile (high speed with no need for licence and better operation in fog, compared to λ = 1.55 μm)





R. Martini et al., IEE Elect. Lett. 37 (11), p. 1290, 2001.
S. Blaser et al., IEE Elect. Lett. 37 (12), p. 778, 2001.

Main application: chemical sensing by optical spectroscopy

Detection techniques already demonstrated using QCL:

- photo-acoustic
  - B. Paldus et al., Opt. Lett. 24 (3), p.178, 1999.
  - D. Hofstetter et al., Opt. Lett. 26 (12), p. 887, 2001.
  - M. Nägele et al., Analytical Sciences 17 (4), p. 497, 2001.
- TILDAS
  - M. Zahniser et al. (Aerodyne Research), TDLS'03.
- cavity ringdown
  - B. Paldus et al., Opt. Lett. 25 (9), p. 666, 2000.
- absorption spectroscopy
  - A. Kosterev et al., Appl. Phys. B 75 (2-3), p. 351, 2002.
- heterodyne detection scheme
  - D. Weidmann et al., Opt. Lett. 29 (9), p. 704, 2003.
- cavity enhanced spectroscopy
  - D. Bear et al. (Los Gatos Research), TDLS'03.

Some needs:

high-power laser

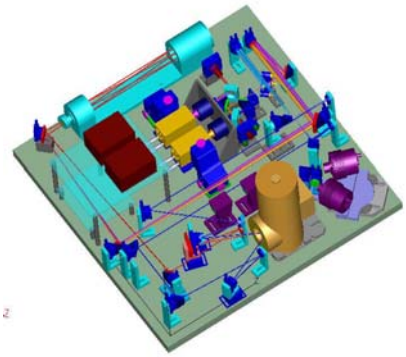
single mode

continuous-wave

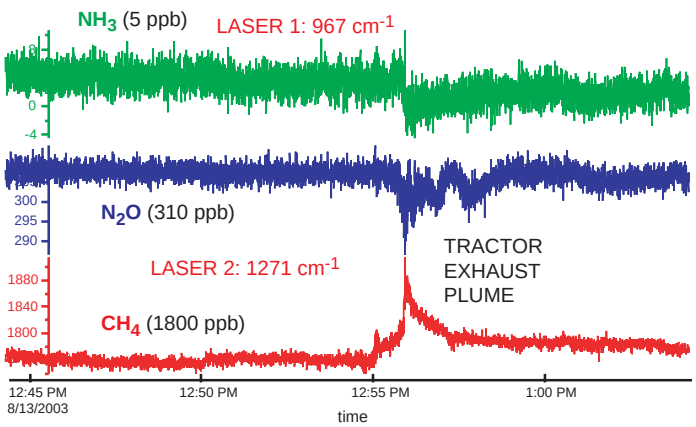
Application fields

- Chemical sensing or trace gas measurements
  - process development
  - environmental science
  - forensic science
  - process gas control
  - liquid detection spectroscopy
- Medical diagnostics
  - breath analyzer
  - glucose dosage
- Remote sensing
  - leak detection
  - exhaust plume measurement
  - combat gas detection

Simultaneous 3-gas measurements with dual-laser QCL instrument

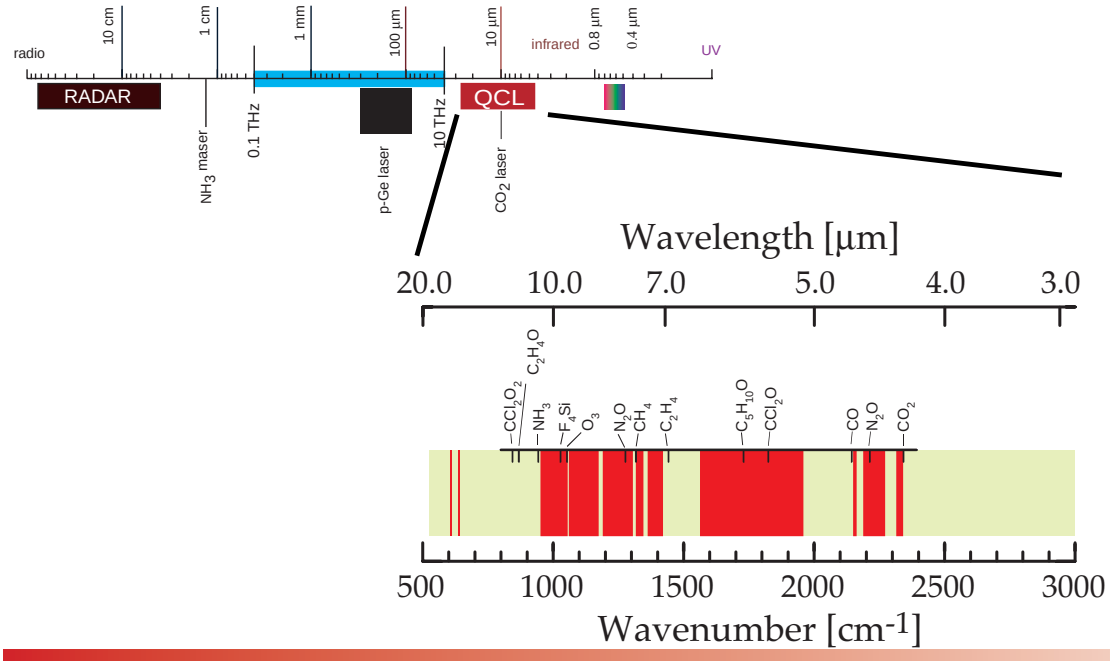


Two QC-lasers from Alpes:
2 to 6 gases (CH_4, N_2O, NH_3)
56 m cell path length
Detector options



M. Zahniser et al.,
Aerodyne Research Inc., Billerica (USA)

Spectrum covered by Alpes Lasers dfb QCLs

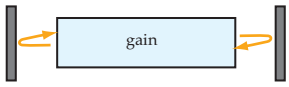


Alpes Lasers

Single-mode operation: distributed-feedback QCLs

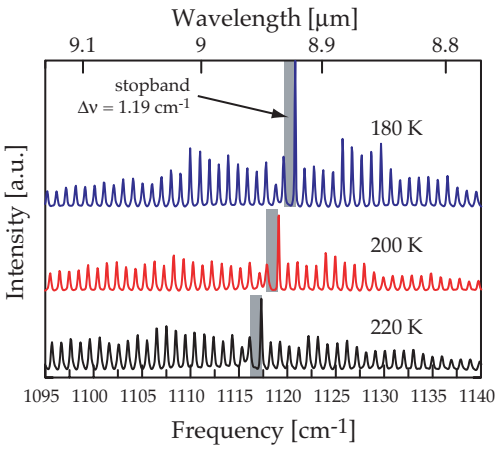
How does a DFB work?

Fabry-Pérot laser:



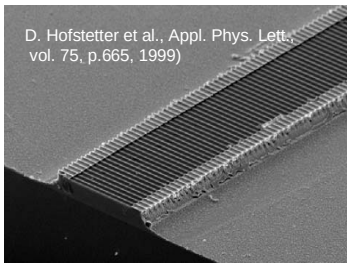
Amplified light bounces in the cavity

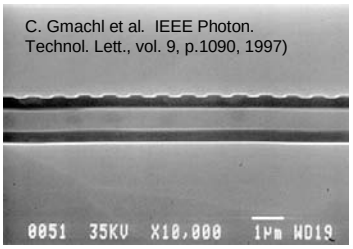
DFB:
periodic grating => waves coupling
=> high wavelength selectivity



complex-coupled DFB:
- lasing mode closest to the stopband
- stopband ≈ coupling strength

Distributed-feedback technologies





Grating on the surface (open-top)

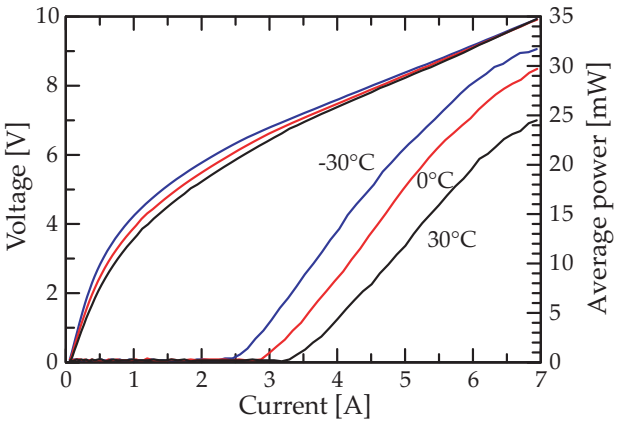
- one MBE run (no MOCVD)
- high peak power (large stripes) but low average power
- optical losses due to metalization

Grating close to active region

- lower thermal resistance (high duty / high temperature)
- high average power
- higher overlap, smaller losses
- jct dn mounting possible
- needs MOCVD regrowth

High average power DFB QCL — RT-HP-DFB-20-1200

Distributed feedback QC laser at 8.35µm with InP top cladding



Characteristics

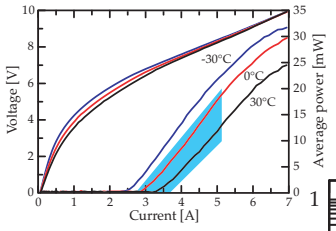
3mm-long, 28µm-wide laser
$\lambda \approx 8.35$ µm

@-30°C: Average power (2% dc):
P = 32 mW (1.6 W peak power)
threshold current:
I_{th} = 2.44 A (j_{th} = 2.9 kA/cm^2)

@30°C : P = 25 mW (1.25W peak power)
I_{th} = 3.2 A (j_{th} = 3.8 kA/cm^2)

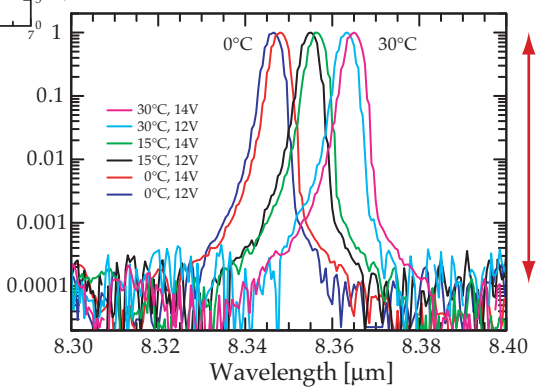
Alpes Lasers

High average power DFB QCL — RT-HP-DFB-20-1200



Characteristics

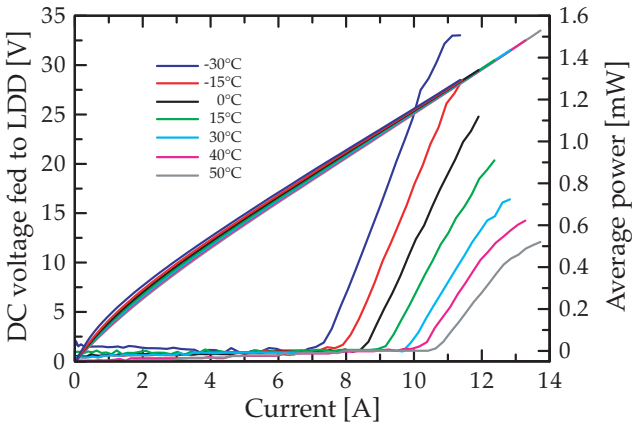
Entire tuning range:
$\Delta\nu$ = 5.7 cm^{-1} at 1197 cm^{-1} (0.47%)
(1195.2 cm^{-1} (8.367 µm) at 30°C to 1200.9 cm^{-1} (8.327 µm) at -30°C)



40 dB (limited by the grating spectrometer)

Long-wavelength (λ≈16.4μm) B2C DFB QCL RT-P-DFB-1-608

Laser based on a bound to continuum design, λ ≈ 16.4 μm
Rochat et al., APL **79**, 4271 (2001)



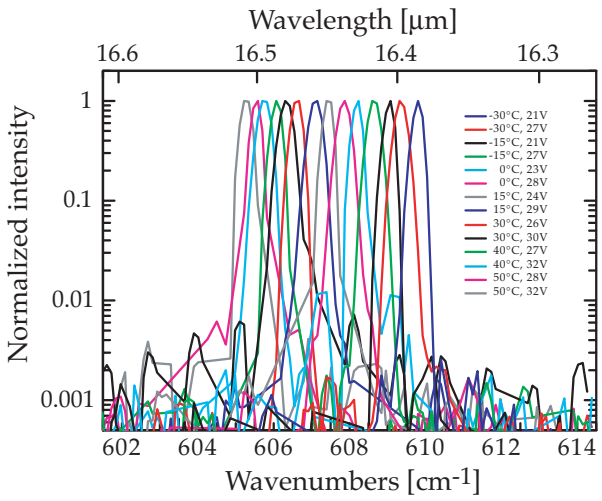
Characteristics

3 mm-long, 44μm-wide laser
λ ≈ 16.4 μm

@-30°C: Average power (1.5% dc):
P = 1.5 mW (100 mW peak power)
Threshold current:
Ith = 7.1 A (j_{th}=5.4 kA/cm^2)

@50°C : P = 0.5 mW (33 mW peak power)
Ith = 10.4 A (j_{th}=7.9 kA/cm^2)

Long-wavelength (λ≈16.4μm) B2C DFB QCL RT-P-DFB-1-608



Characteristics

3mm-long, 44μm-wide laser
λ ≈ 16.4 μm

Single-mode emission:
Side Mode Suppression Ratio > 25 dB
(limited by the resolution of the FTIR)

Tuning range:
Δν = 4.5 cm^{-1} at 608 cm^{-1} (0.7%)

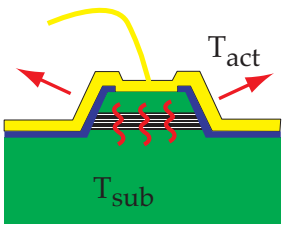
(605.76 cm^{-1} (16.51 μm) at 50°C to
610.30 cm^{-1} (16.38 μm) at -30°C)

How does a DFB tune?

How does a DFB tune?

Tuning always due to thermal drift

(carrier effects can be neglected!)

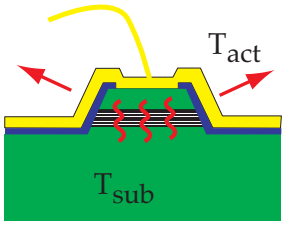


wavelength selection : $\lambda = 2 \cdot n_{eff} \cdot \Lambda_{grating}$

$n_{eff} = n_{eff}(T)$

$$\frac{d\lambda}{\lambda} = \frac{dn_{eff}}{n_{eff}}$$

How does a DFB tune?



Active region heating:

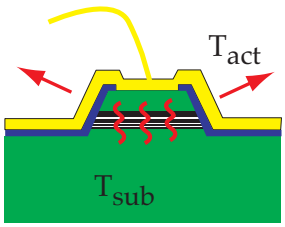
$$T_{act} = T_{sub} + I \cdot U \cdot \delta \cdot R_{th} \left(+ I_{DC} U_{DC} \cdot R_{th}\right)$$

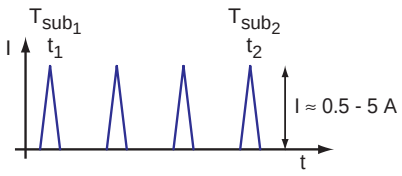
$$\Delta T = T_{act} - T_{sub}$$

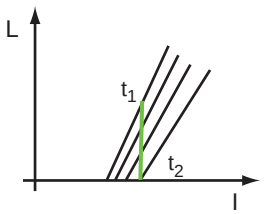
If ΔT = 100°C ⇨ 100% chance of laser-destruction (thermal stress)
= 60°C ⇨ depends of mounting / laser -> dangerous
= 30°C ⇨ OK

Different possibilities of thermal tuning:
- substrate temperature
- additional bias current
- pulse length (chirping)
- pulse current
- duty-cycle

Tuning by changing T_{sub} (heatsink temperature)







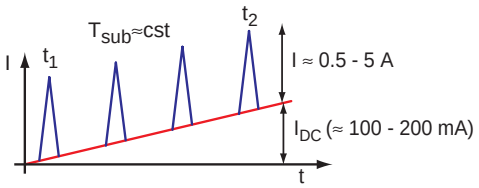
tuning coefficient :

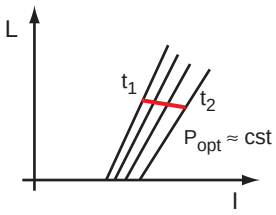
$$\frac{1}{\lambda}\frac{\Delta\lambda}{\Delta T_{sub}} = \frac{1}{n_{eff}}\frac{\Delta n_{eff}}{\Delta T_{sub}} \approx [6-7]\cdot 10^{-5}\ K^{-1}$$

$\Delta T \approx 60°C$ => -0.4% $\Delta\nu/\nu$ @ 0.01Hz

Tuning by DC bias-induced heating

by DC bias-induced heating

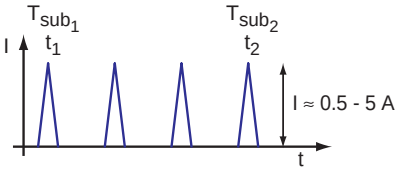


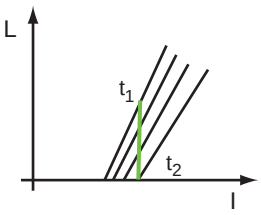


$$R_{th} = \frac{\Delta T}{V_{device} \cdot I_{DC}}$$

ΔT ≈ 30°C => -0.2% Δν/ν @ >1kHz

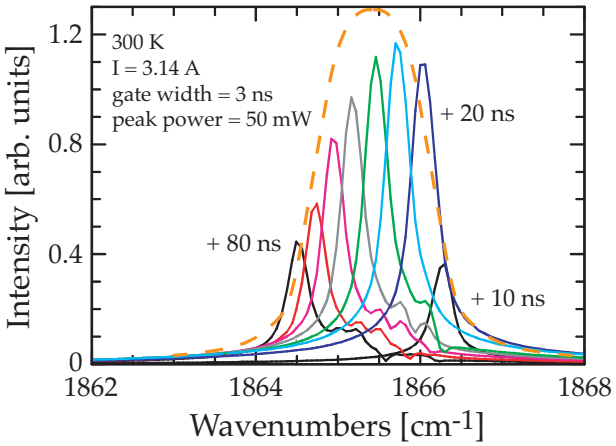
by changing T_{sub}





ΔT ≈ 60°C => -0.4% Δν/ν @ 0.01Hz

Thermal chirping during pulse

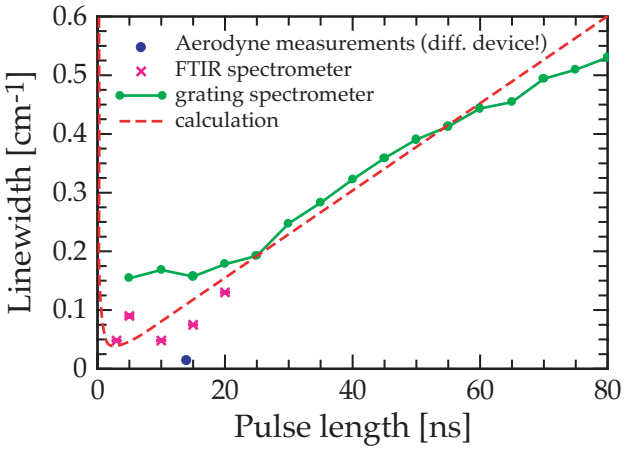


Faist et al., Appl. Phys. Lett. 70, p.2670 (1997)

drift with time: 0.03 cm^{-1}/ns (high dissipated power)

20 K temperature increase of during a 100-ns-long pulse

Pulse length dependence of linewidth



Hofstetter et al., Opt. Lett. 26, p.887 (2001)

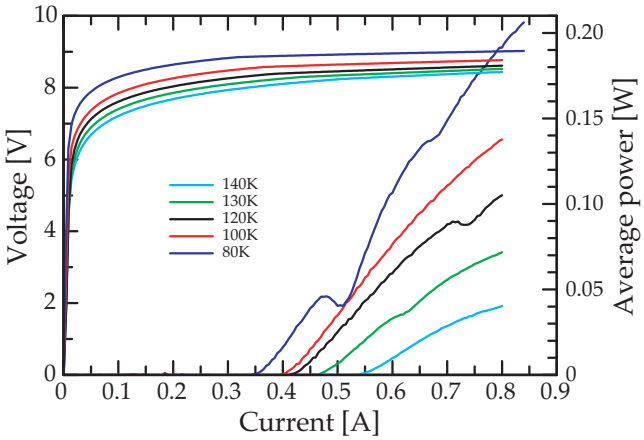
Need for a good compromise:
• too long: limited by thermal chirping
• too short: limited by the time evolution of the lasing mode

⇨ fundamental limits

⇨ for narrower linewidth: cw operation

CW operation at λ ≈ 6.73μm

LN2-CW-DFB-100-1485



Characteristics

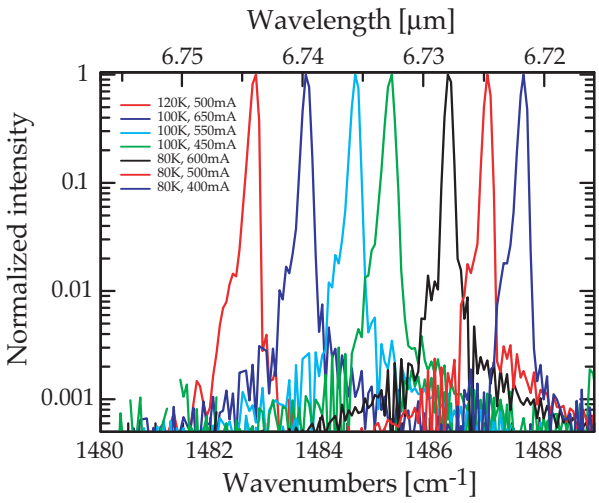
1.5 mm-long, 23 μm-wide laser
CW operation at λ ≈ 6.73 μm

@80 K: Average power P = 0.2 W
Threshold current:
Ith = 0.35 A (j_{th} = 1.0 kA/cm^2)

I_{op} < 0.8 A
U_{op} < 9 V

CW operation at λ ≈ 6.73µm

LN2-CW-DFB-100-1485



Characteristics

1.5 mm-long, 23 µm-wide laser
CW operation at λ ≈ 6.73 µm

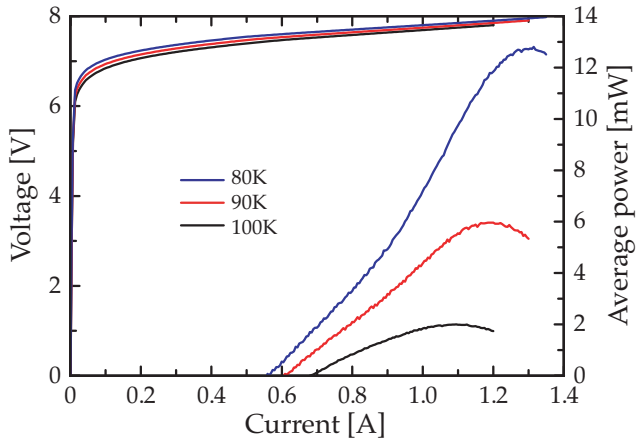
Single-mode emission:
Side Mode Suppression Ratio > 30 dB
(limited by the resolution of the FTIR)

Tuning range:
$\Delta\nu$ = 4.9 cm^{-1} at 1485 cm^{-1} (0.33%)

(1482.8 cm^{-1} (6.744 µm) at 120K to
1487.7 cm^{-1} (6.722 µm) at 80K)

CW operation at λ ≈ 4.60µm

LN2-CW-DFB-10-2171



Characteristics

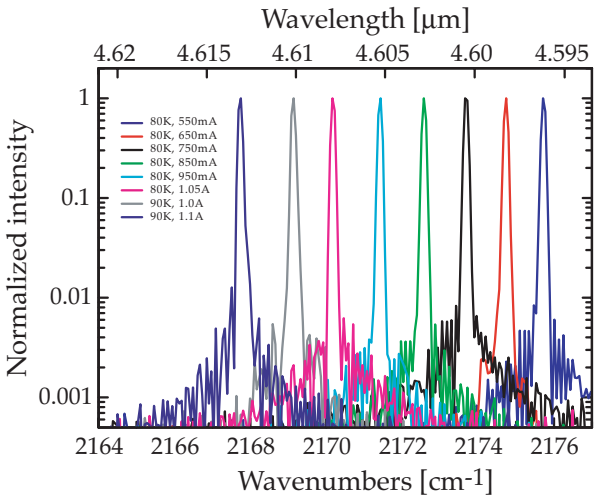
1.5 mm-long, 21 µm-wide laser
CW operation at λ ≈ 4.60 µm

@80 K: Average power P = 12 mW
Threshold current density:
Ith = 0.54 A (j_{th} = 1.7 kA/cm^2)

I_{op} < 1.1 A
U_{op} < 8 V

CW operation at λ ≈ 4.60μm

LN2-CW-DFB-10-2171



Characteristics

1.5 mm-long, 21 μm-wide laser
CW operation at λ ≈ 4.60 μm

Single-mode emission:
Side Mode Suppression Ratio > 25 dB
(limited by the resolution of the FTIR)

Tuning range:
$\Delta\nu$ = 8 cm^{-1} at 2171 cm^{-1} (0.37%)

(2167.7 cm^{-1} (4.613 μm) at 90K to
2175.7 cm^{-1} (4.596 μm) at 80K)

Alpes Lasers

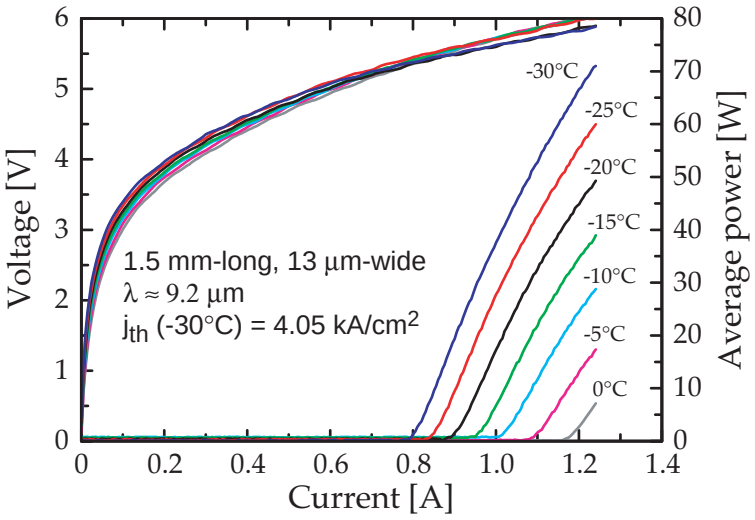
Future:

continuous-wave and single-mode operation at room-temperature

terahertz sources

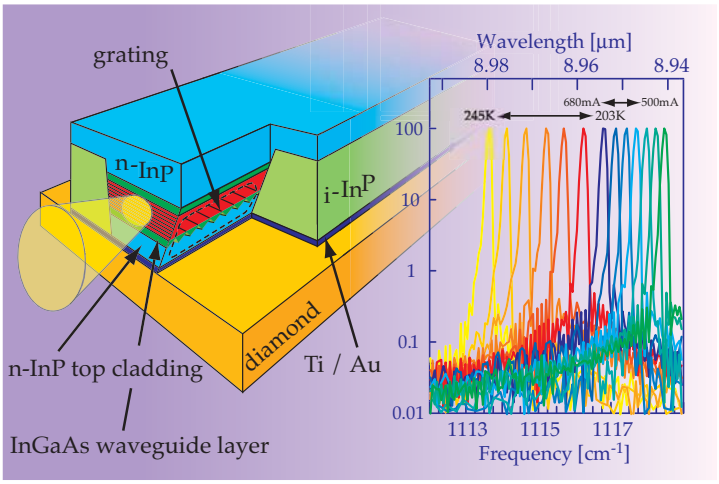
Continuous-wave FP QCL on Peltier

RT-CW-FP-50-1080



I_{op} < 1.2 A
U_{op} < 6 V

BH distributed-feedback QCLs



Continuous-wave distributed-feedback quantum-cascade lasers on a Peltier cooler: T. Aellen, S. Blaser, M. Beck, D. Hofstetter, J.Faist, and E. Gini, Appl. Phys. Lett. **83**, p.1929, 2003.

THz applications

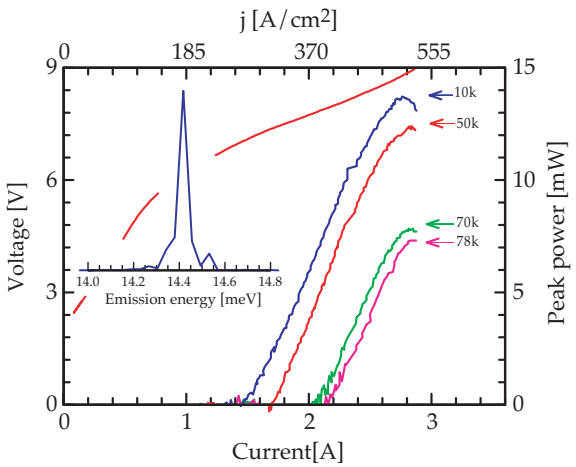
New sources: R. Köhler et al., Nature 417, p.156, 2002.
M. Rochat et al., Appl. Phys. Lett. 81 (8), p.1381, 2002.

Terahertz applications:

- Astronomy
- Medical imaging
- Chemical detection
- Telecommunications for local area network (LAN)

Terahertz sources

THz QC laser based on a bound to continuum design, $\lambda \approx 87$ μm
Structure grown at University of Neuchâtel (G. Scalari, L. Ajili, M. Beck and M. Giovannini)



Characteristics

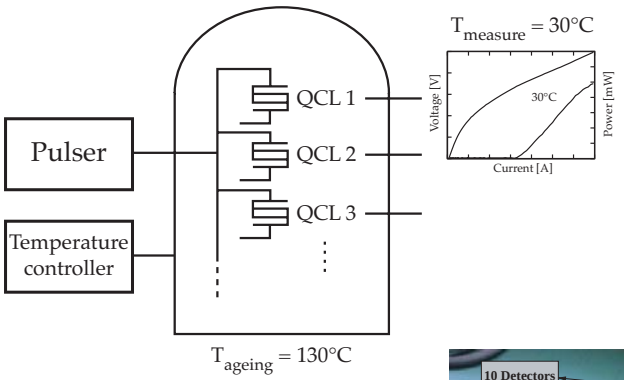
THz QC laser: $\lambda \approx 87$ μm
2.7mm-long, 200μm-wide laser
back-facet coated

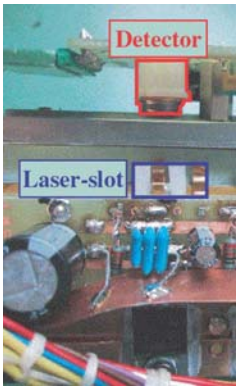
@10 K: Peak power (2.5% dc):
P = 14 mW
threshold current density:
j_{th} = 267 A/cm^2

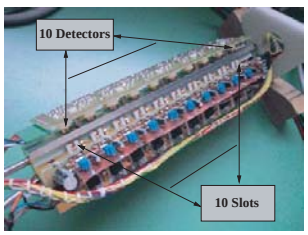
pulsed operation up to 78K
CW operation up to 30 K

Reliability of the devices

Reliability of the devices: ageing







Ageing: theory

Conversion of lifetime using Arrhenius type relation: $t \sim \exp[E/(kT)]$

where: t is lifetime
T temperature
E=0.7 eV activation energy [H. Ishikawa et al., J. Appl. Phys. **50**, 1979]
(needs to be evaluated for QCL)

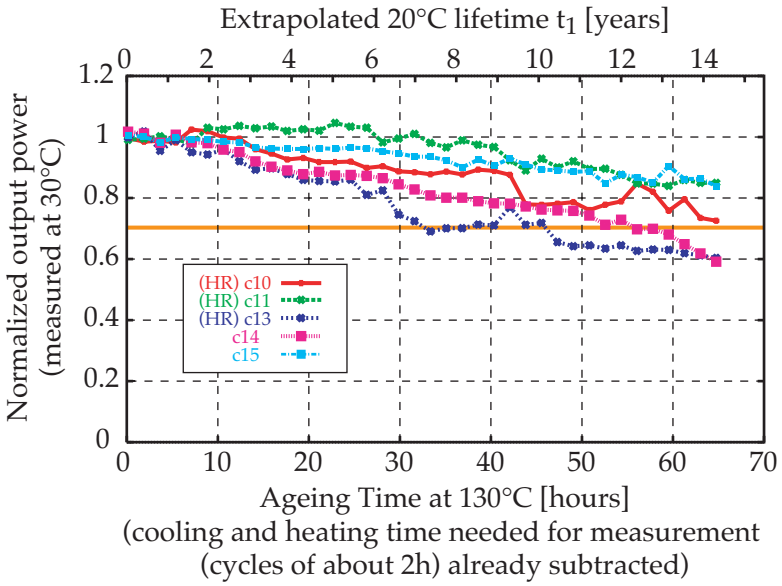
The room temperature lifetime t_1 (at T_1 = 20°C and 70% of initial power) can be extrapolated by :

$$t_1 = t_0 \cdot e^{\frac{E}{k} \cdot \frac{1}{T_1} - \frac{1}{T_0}}$$

with t_0 is the measured lifetime at the ageing temperature T_0 (here 130°C = 403K).

(using 100°C for example it will take 5 times longer)
80°C 17

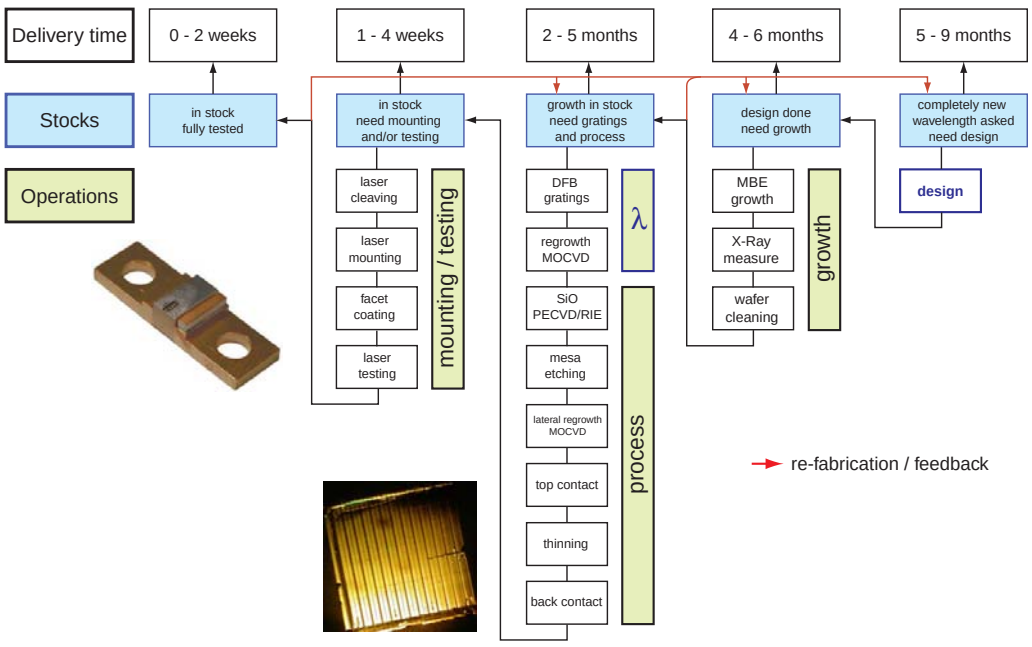
Ageing at 130°C: results



Production

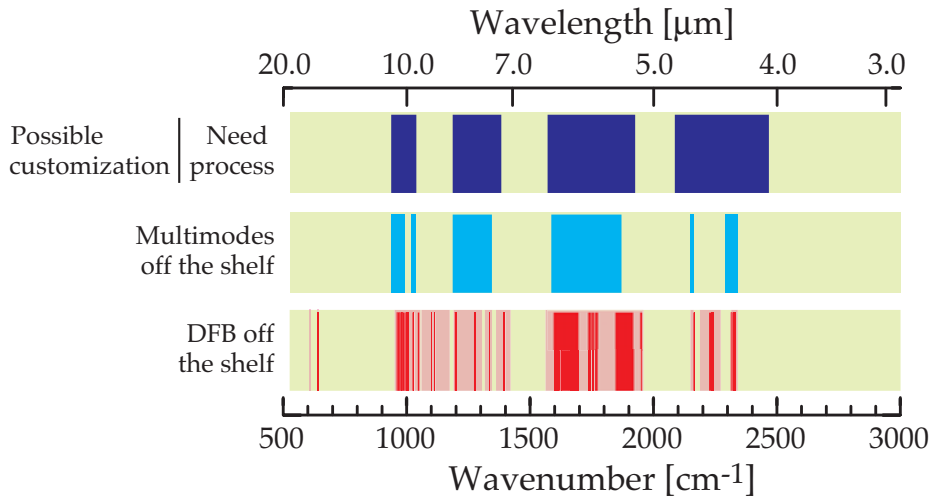
Boston Electronics * QCL@boselec.com

Production line



Boston Electronics * QCL@boselec.com

Production - lasers off the shelf

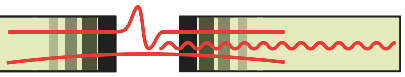


for an up to date wavelength listing, contact us at: http://www.alpeslasers.ch

List of products - prices

Type	Duty-cycle	Operating temp.	Product name	Power	Linewidth	Tunability	Off the shelf	Built to order	100+
DFB	pulsed	RT	RT-HP-DFB-2-X	> 2 mW	< 330 MHz	0.4%	11 kEUR	28 kEUR	
			RT-HP-DFB-5-X	> 5 mW			13.5 kEUR		
	cw	LN_2	LN2-CW-DFB-2-X	> 2 mW	< 3.5 MHz	0.4%	23.5 kEUR	50 kEUR	
	cw	RT	RT-CW-DFB-2-X	> 2 mW	< 3.5 MHz	0.4%	available end 2004		
FP	pulsed	RT	RT-HP-FP-10-X	> 10 mW	1 - 4 %	N/A	6 kEUR		
	pulsed	LN_2	LN2-HP-FP-150-X	> 150 mW	1 - 4 %	N/A	20 kEUR		
	cw	RT	RT-CW-FP-5-X (only at 9.1µm)	> 5 mW	1 - 4 %	N/A	17 kEUR		

http://www.alpeslasers.ch



Conclusion / outlook

Available products

- pulsed DFB QCL on Peltier cooler in the range of 4.3μm to 16.5μm
- LN_2 continuous-wave DFB QCL in the range of 4.6μm to 10μm
- continuous-wave FP on Peltier cooler at 9.1μm

Soon available

- THz sources (LN_2)

Available end 2004

- continuous-wave DFB on Peltier cooler
  (already demonstrated: T. Aellen, S. Blaser, M. Beck, D. Hofstetter, J.Faist, and E. Gini, Appl. Phys. Lett. **83**, p.1929, 2003)

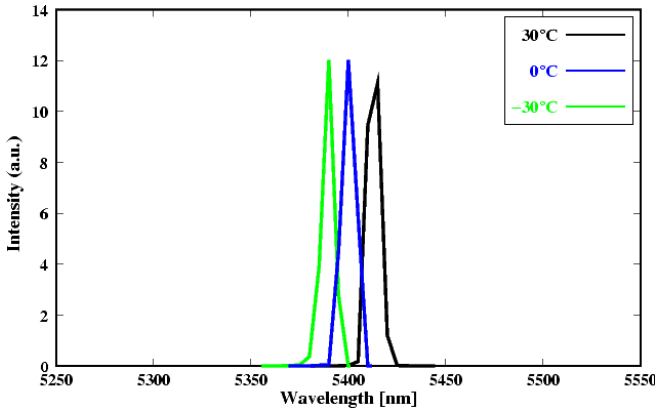
Boston Electronics * QCL@boselec.com

Alpes Lasers

PRODUCTS

Distributed Feedback Laser (Single mode)

- Operation in pulsed mode
- Two different mountings available:
  - TH mounting (bolt down) Size: 20 x 6 x 3.2 mm^3
  - SB mounting (clamp-holder) Size: 19 x 7 x 2 mm^3
- Room temperature operation
- Output power:
  - Average: 2 - 10 mW
  - Peak: 100 - 500 mW
- Beam divergence (full angle):
  - 60° perpendicular
  - 40° parallel

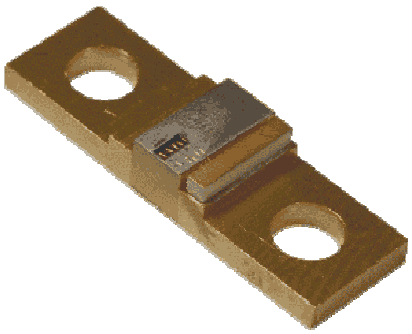


Available wavelengths:

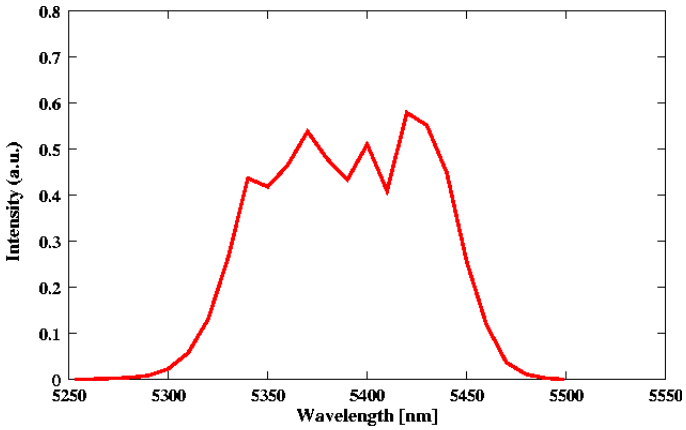
5.3 - 6.0 µm and 10.0 - 10.5 µm

Lead time 2-8 weeks

Fabry-Perot Laser (Multimode)



- Operation in pulsed mode
- Two different mountings available:
    - TH mounting (bolt down)
      Size: 20 x 6 x 3.2 mm^3
    - SB mounting (clamp-holder)
      Size: 19 x 7 x 2 mm^3
- Room temperature operation
- Output power:
    - Average: 2 - 10 mW
    - Peak: 100 - 500 mW
- Beam divergence (full angle):
    - 60° perpendicular
    - 40° parallel



Lead time 2-8 weeks

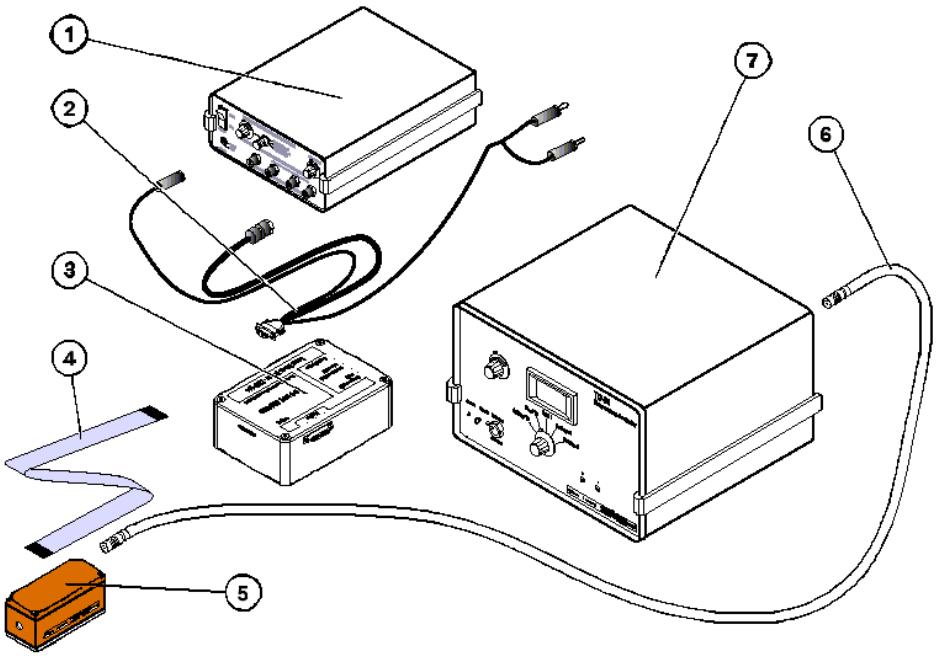
Available wavelengths:

5.0 - 6.2 µm and 8.5 - 10.5 µm

Starter kit

Equipment for operating Distributed-Feedback-Laser and Fabry-Perot-Laser.

Overview:



This kit contains: (1) Pulse generator, (2) connector cable to (3) pulse switcher, (4) low impedance line conducting pulses to (5) laboratory laser housing. Power supply of internal cooling elements via (6) connector cable by (7) temperature controller.

Lead Time 2 weeks

How to get started:
Just place the laser into the thermally stabilized Laboratory Laser Housing and connect your own external DC-power supply (30V, 1A..50V, 2A; depending on the laser).

Laboratory Laser Housing - LLH

- Peltier cooled laser-stage inside, minimal temperature <-30°C
- Laser power supply by low impedance line from LDD
- Anti Reflection Coated (3.5 to 12 µm) ZnSe window.
- Exchangeable laser sub mount.
- Direct voltage measurement on the laser connection, AC coupled.
- PT-100 or NTC temperature measurement.
- Needs air or water-cooling.
- Temperature stabilization and power supply by TC51
    - Size: 10cm x 5cm x 5cm

Low impedance line

- Length: 0.5m

Lead time 2 weeks

Laser Diode Driver - LDD100

- Peak Current up to 15 Amps
- Voltage up to 50 Volts
- Low impedance connection to LLH
- 12 V DC power supply, provided by pulse generator
- TTL 50 Ohm input
- Monitor: laser voltage, current, pulse frequency & duty cycle.
- Rise/fall time 10 ns
- Pulse duration min 10ns (with attenuation), flat from 20ns to DC
- Pulse repetition rate 0 to 1 MHz (possible to 2 MHz, but not linear)
- Size: 15cm x 6cm x 9 cm

Lead time 2 weeks

LDD supply cable

- Length: 2.0m

Lead time 2 weeks

Pulse Generator - TPG128

- Two TTL 50 Ohm output
- Synchronization output
- Rise/fall time < 10 ns
- Pulse duration 20 to 200 ns
- Pulse repetition rate 10 kHz to 5 MHz
- Gate input
- Power supply 220V, 50-60 Hz
- This unit drives the LDD (duty cycle up to 20%)
- Size: 22cm x 7cm x 13.5cm

Lead time 2 weeks

Temperature Controller - TC51

- Temperature range: -35°C .. +65°C
- PT100 temperature sensor
- Internal/External temperature setting
- Monitor-output for real temperature
- Laser overheat-protection by Interlock-system
- This unit stabilizes temperature of laser in LLH

- Size: 11.5cm x 22cm x 27.5cm

Connector cable TC51 - LLH

- Length: 1.3m
- provides current for Peltier elements and connects Pt-100 sensor to TC-51

Lead time 2 weeks

Alpes Lasers

APPLICATIONS

Fields of applications:

Quantum cascade lasers have been proposed in a wide range of applications where powerful and reliable mid-infrared sources are needed. Examples of applications are:

Industrial process monitoring:

Contamination in semiconductor fabrication lines, food processing, brewing, combustion diagnostics.

Life sciences and medical applications

Medical diagnostics, biological contaminants.

Law enforcement

Drug or explosive detection.

Military

Chemical/biological agent detection, counter measures, covert telecommunications.

Why the mid-infrared?

Because most chemical compounds have their fundamental vibrational modes in the mid-infrared, spanning approximately the wavelength region from 3 to 15µm, this part of the electromagnetic spectrum is very important for gas sensing and spectroscopy applications. Even more important are the two atmospheric windows at 3-5µm and 8-12µm. The transparency of the atmosphere in these two windows allows remote sensing and detection. As an example, here are the relative strengths of CO_2 absorption lines as a function of frequency:

Wavelength (µm)	Relative absorption strength
1.432	1
1.602	3.7

2.004	243
2.779	6800
4.255	69000

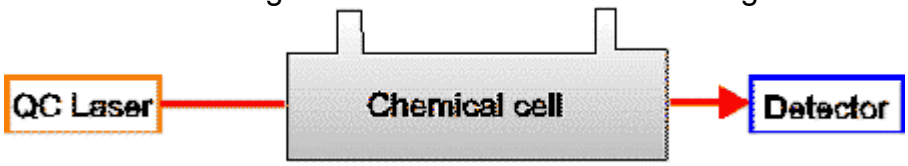
Approximate relative line strengths for various bands of the CO_2 gas.

Moreover, because of the long wavelength, Rayleigh scattering from dust and rain drops will be much less severe than in the visible, allowing applications such as radars, ranging, anti-collision systems, covert telecommunications and so on. As an example, Rayleigh scattering decreases by a factor 10^4 between wavelengths of 1µm and 10µm.

Detection techniques

Direct absorption

In a direct absorption measurement, the change in intensity of a beam is recorded as the latter crosses a sampling cell where the chemical to be detected is contained. This measurement technique has the advantage of simplicity. In a version of this technique, the light interacts with the chemical through the evanescent field of a waveguide or an optical fiber.

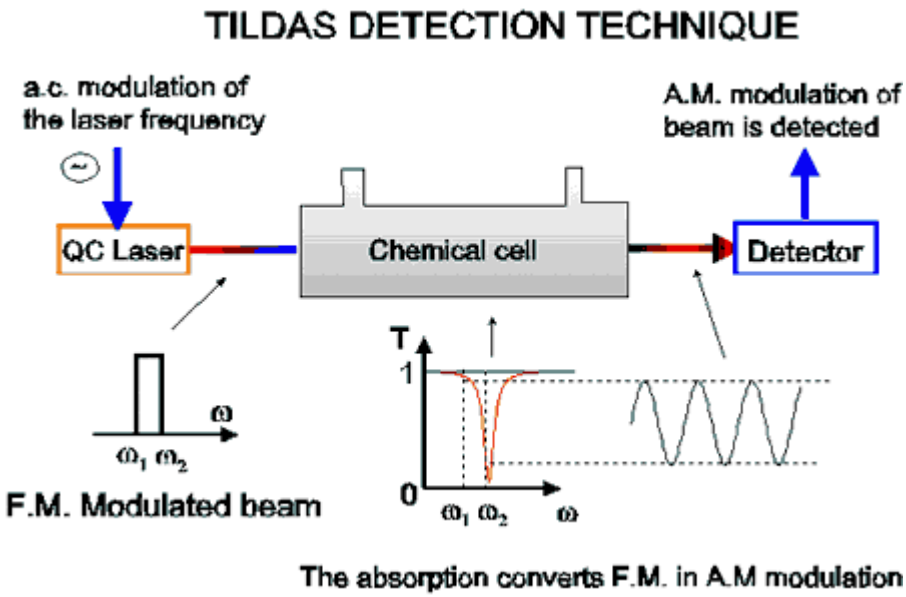


Some examples of use a direct absorption technique:

- A. Müller et al. 1999 (PDF 1187kB)
- B. Lendl et al.

Frequency modulation technique (TILDAS)

In this technique, the frequency of the laser is modulated sinusoidally so as to be periodically in and out of the absorption peak of the chemical to be detected. The absorption in the cell will convert this FM modulation into an AM modulation, which is then detected usually by a lock-in technique.

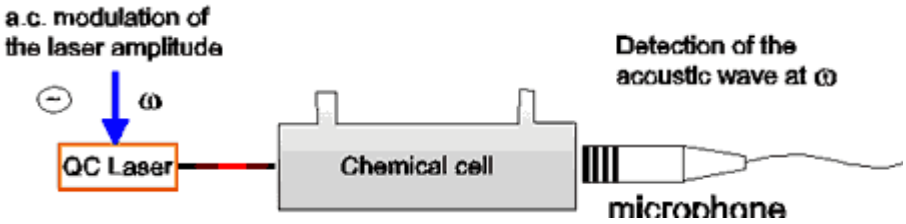


The advantage of the TILDAS technique is mainly its sensitivity. First of all, under good modulation condition, an a.c. signal on the detector is only present when there is absorption in the chemical cell. Secondly, this signal discriminates efficiently against slowly varying absorption backgrounds. For this reason, this technique will usually work well for narrow absorption lines, requiring also a monomode emission from the laser itself. This technique has already been successfully applied with Distributed Feedback Quantum Cascade Laser (DFB-QCL). Some examples in the literature include:

- E. Whittaker et al, Optics Letters 1998 (PDF 229kB)
- F. Tittel et al., accepted for publication in Optics Letters.

Photoacoustic detection

In the photoacoustic technique, the optical beam is periodically modulated in amplitude before illuminating the cell containing the absorbing chemical. The expansion generated by the periodic heating of the chemical creates an acoustic wave, which is detected by a microphone. The two very important advantages of photoacoustic detection are
i) a signal is detected only in the presence of absorption from the molecule
ii) no mid-ir detectors are needed.
For these reasons, photoacoustic detection has the potential of being both cheap and very sensitive. However, ultimate sensitivity is usually limited by the optical power of the source.



Photoacoustic detection has already been used successfully with unipolar laser, see

- Paldus et al., Optics Letters ...

Customers

Our list of customers includes:

Jet Propulsion Laboratory (USA), Vienna University of Technology (Austria), Fraunhofer Institute (Germany), Georgia Institute of technology (USA), ETHZ (Switzerland), Physical Sciences Inc. (USA): first QCL based product, Aerodyne (USA), Scuola Normale de Pisa (Italy), Orbisphere (Switzerland).

Alpes Lasers

TECHNOLOGY

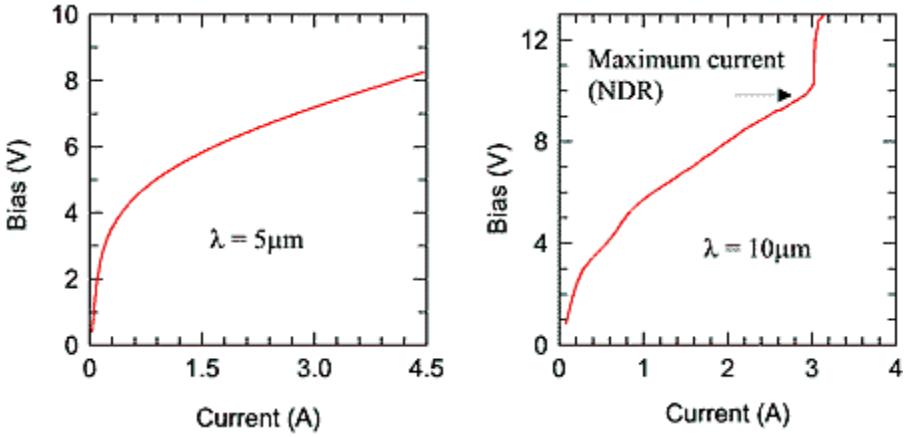
General device characteristics

How do I drive the device?

As for any semiconductor laser, the performance of the device depends on the temperature. In general, unipolar lasers need (negative) operating voltage around 10 V with (peak-) currents between 1 and 5 A, depending on the temperature and the device. Around room temperature, that is the temperature range (-40..+70 °C) that can be reached by Peltier elements, unipolar lasers operate only in pulsed mode because of the large amount of heat dissipated in the device. In general, pulse length around 100 ns is suitable for Fabry Pérot devices. Alpes Lasers sells electronic drivers dedicated to unipolar lasers.

Electrical behavior and I-V characteristics

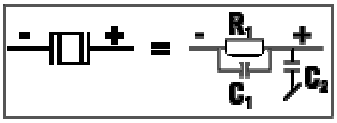
Quantum cascade lasers exhibit I-V curves that are diode like characteristics for short wavelength devices (l = 5 µm) to almost ohmic behavior for l = 11 µm. In any case the differential resistance at threshold is a few ohms. Long wavelength devices often exhibit a maximum current above which, if driven harder, the voltage increases abruptly while the optical power drops to zero. This process, which occurs only in unipolar lasers, is usually non-destructive and reversible if the device is not driven too hard above its maximum current.



Room temperature I-V curves of unipolar lasers (measured in pulsed mode). The device operating at l = 10 µm has a maximum operation current (because of the appearance of Negative Differential Resistance or NDR) of 3.2 A.

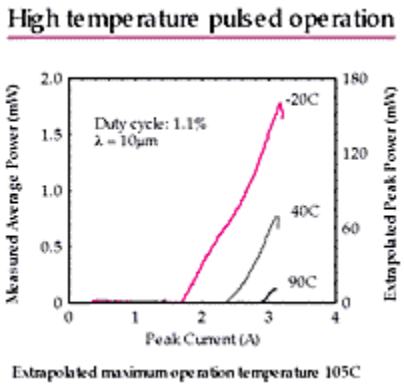
Electrical model:

In a simplified way, the device can be modeled, for electronic purpose, by a combination of two resistors and two capacitors. As shown by the above I-V curves, R1 increases from 10 to 20 Ohms at low biases to 1-3 Ohms at the operating point. C1 is a 100-pF capacitor (essentially bias independent) between the cathode and the anode coming from the bonding pads. C2 depends on your mounting of the laser typically in the Laboratory Laser Housing, C1<100 pF

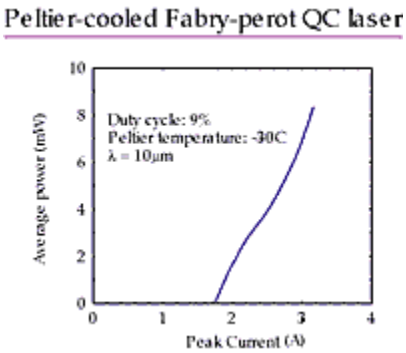


Temperature dependence of the laser characteristics:

The threshold current and slope efficiency are temperature dependent, although this dependence is much weaker than the one observed in interband devices at similar wavelengths. Shown below are a set of power versus current curves taken from a device l = 10 µm at various temperatures. In general, the device has a maximum operation temperature, which, depending on the design and wavelength, can be between 300K to a maximum of 400K. As maximum power and sometimes slope efficiencies both increase with decreasing temperature, it is usually advisable to cool the device with a Peltier element. Alpes Lasers sells a special Peltier cooled housing dedicated to driving unipolar lasers. Peak power between 20 and 100 mW, which is equal to average powers between 2 and 10 mW, are obtained typically.



Peak and average power (at a duty cycle of 1.5%) for a unipolar laser as a function of temperature.

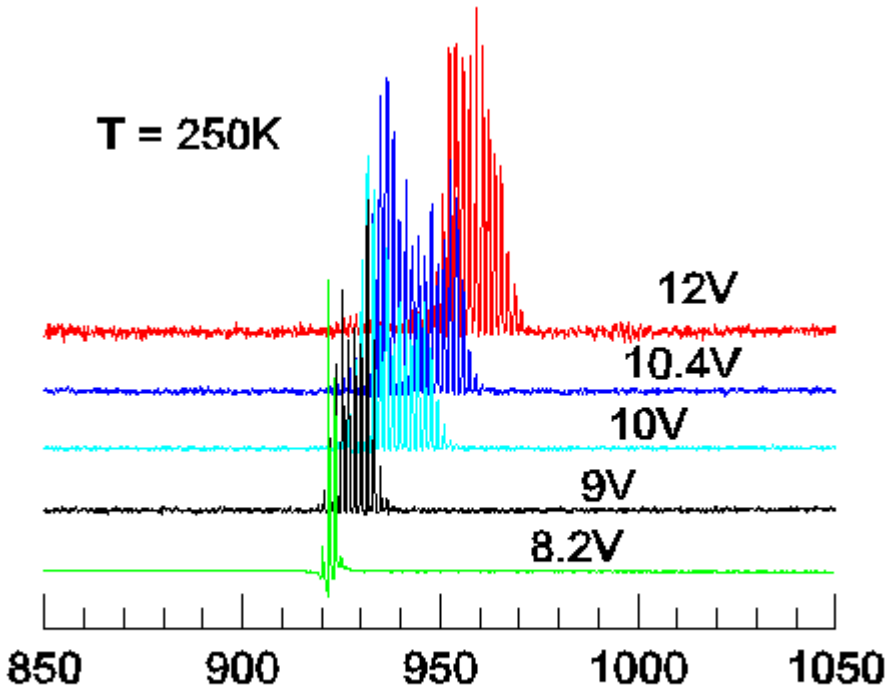


High duty cycle operation of a unipolar laser

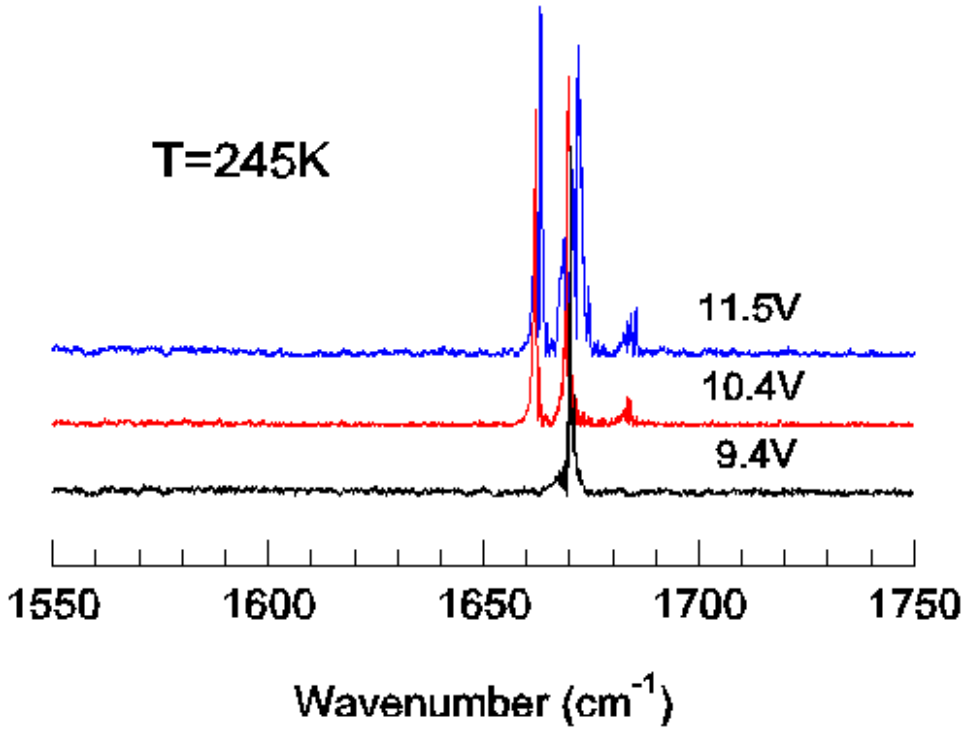
Typically, because of excess heat due to the driving current, unipolar lasers must be driven by current bursts with typically 10 ns rise time and a pulse-length of 100 ns. Some unipolar lasers may also operate in continuous wave (c.w.) at cryogenic temperatures, with a maximum operating temperature of 50 to 100 K depending on the design.
Alpes Lasers specify c.w. operation on special request.

Spectral characteristics

Under pulsed operation, the spectra of these lasers are multimode, the spectral width of the emission being of about one to fifty nanometer (1-30 cm^{-1}, typically 10 cm^{-1}) depending on the device design and operating point. Although it is not a property common to all unipolar laser designs, our long-wavelength devices will blue shift with increasing current, as shown on the figure below.



a)



b)

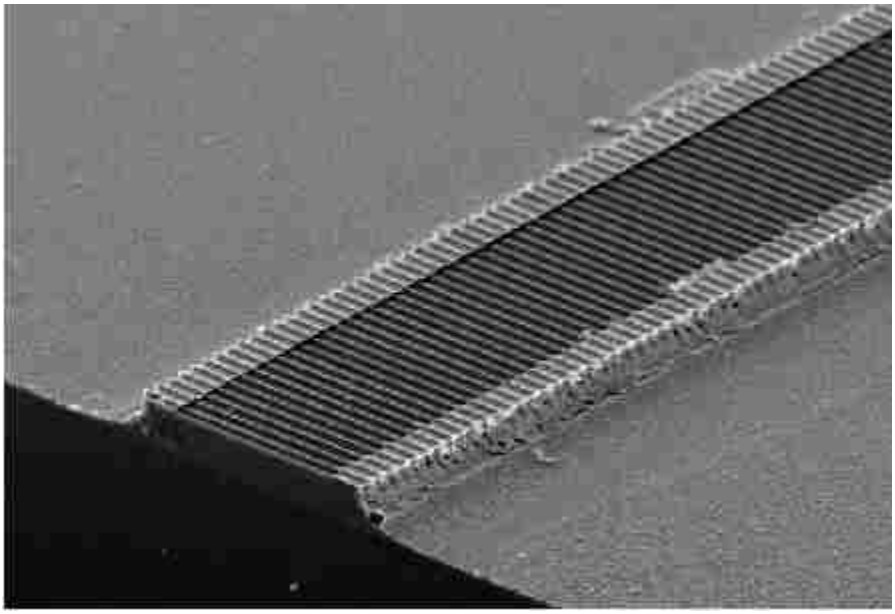
a) spectra of a long wavelength laser based on a diagonal transition
b) spectrum of a short wavelength laser based on a vertical transition

Electrical tuning

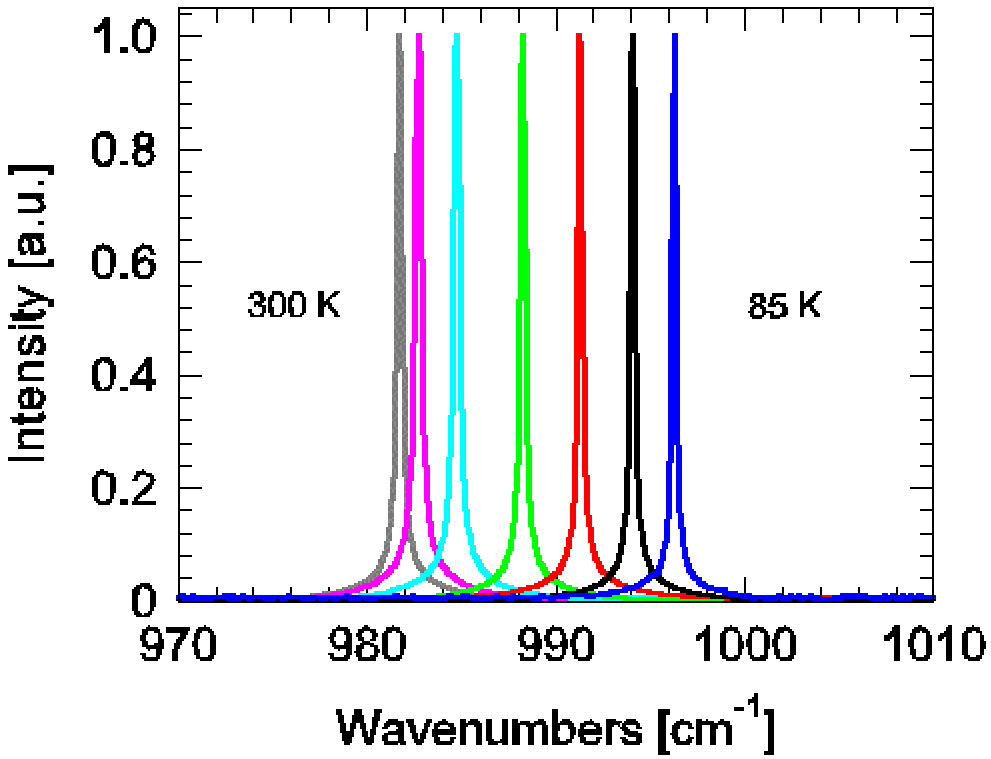
By driving the device with two different electrodes, wavelength and output power can be independently adjusted. Tuning ranges as large as 40 cm^{-1} at a peak power of 5 mW and a temperature of -10 °C have been obtained by Alpes Lasers.
See literature for more details on this technique.

Distributed Feedback Laser (DFB)

In a Distributed Feedback Laser, a grating is etched into the active region to force the operation of the laser at very specific wavelength determined by the grating periodicity. As a consequence, the laser is single frequency which may be adjusted slightly by changing the temperature of the active region with a tuning rate of $1/n\ Dn/DT = 6x10^{-5}K^{-1}$.



Scanning Micrograph image of a Distributed Feedback Unipolar Laser (DFB-UL). The grating selecting the emission wavelength is well visible on the surface.



Emission spectra versus temperature for a DFB-UL. The device is driven at its maximum current.

It must be stressed that because of this tuning effect, when operated in pulsed mode close to room temperature, the linewidth of emission is a strong function of quality of electronics driving the laser. The latter should optimally deliver short pulses (best 1-10 ns to obtain the narrowest lines) with an excellent amplitude stability. The laser will drift at an approximate rate of a fraction of Kelvin per nanosecond during the pulse [see literature].

Beam Properties

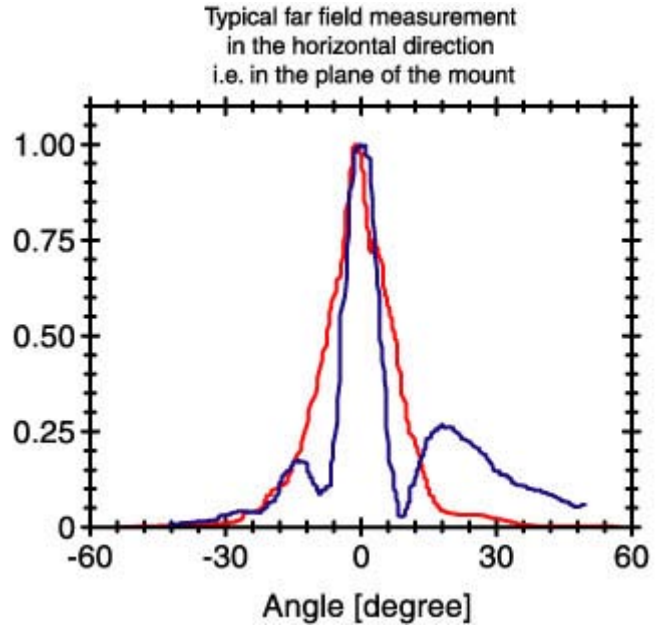
Polarization

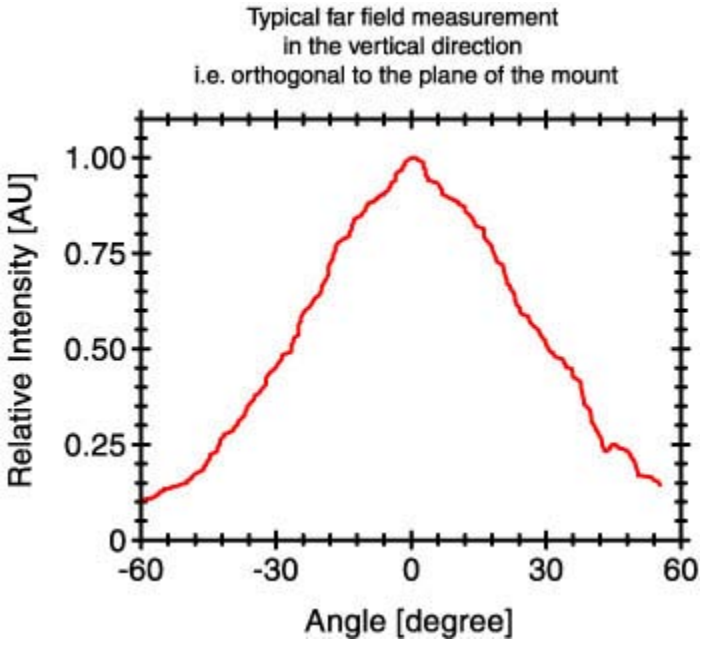
Because the intersubband transition exhibit a quantum mechanical selection rule, the emission from a unipolar laser is always polarized linearly with the electric field perpendicular to the layers (and the copper sub mount).

Beam divergence

The unipolar laser is designed around a tightly confined waveguide. For this reason, the beam diffracts strongly at the output facet and has a (full) divergence angle of about 60 degrees perpendicular to the layer and 40 degrees parallel to the layers

(see figures below). A f#1 optics will typically collect about 70% of the emitted output power. Be careful that the collected output power will decrease with the square of the f-number of the collection optics. The mode is usually very close to a Gaussian 0,0 mode.





QCL FAQ List

Frequently Asked Questions about QC laser systems from Alpes Lasers SA

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This FAQ should address the main questions arising for and from operation of CW and pulsed mode QC lasers from Alpes Lasers SA, especially in combination with the starter-kit. The information given herein is based on best knowledge, but since lasers can behave differently, no guarantee can be given that it will hold true in any case. Contact Alpes Lasers SA in case of doubt or concerning limitations for a particular laser.

The first information source concerning the starter-kit is the corresponding manual. Please read it thoroughly before seeking additional information about the starter-kit.

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1 Mechanical and geometrical properties

QC lasers from Alpes Lasers SA are mounted on special carriers, which require special handling and definition of geometrical orientation.

1.1 Geometry of QC lasers

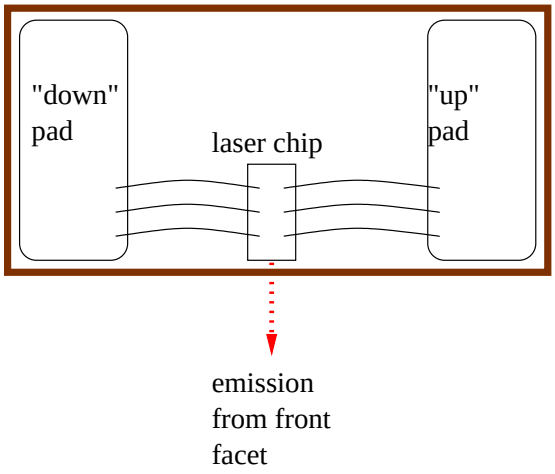
1.1.1 How are the axes of the laser defined, i.e. what is vertical?

The vertical direction is the so called growth direction.

In practice, you have a device in front of you, it is mounted on a copper carrier. The carrier has one or two ceramic pads carrying the bonding wires. The pads are yellow on top due to a layer of gold, and white around it and on the sides (colour of the ceramic). If these pads are placed upwards, the vertical for the laser is the same as the observer vertical direction.

If there are two ceramic pads present, they are named as follows: Looking onto the front facet with the laser placed as described above, the pad left of the laser chip is called "down", the one right of it "up". If no configuration is specified, the "down" pad is used.

Never place the laser upside-down, since this will damage the bonds connecting the pads to the laser!



1.2 How to handle a QCL

1.2.1 How do I store a QCL?

QCLs can be stored at ambient temperature (10..30degC) in normal atmosphere. Humidity should not excess about 80%, and condensation is to be avoided. When operated, only dry atmosphere (below 50% relative humidity) is allowed, and if possible, it should be completely dried (desiccant material, N2 atmosphere).

The laser should always lay flat (with its vertical axis upwards) on a flat and stable surfaces, without touching anything around its circumference. Of course, when mounted in an appropriate and stable holder, it can be operated in any orientation.

1.2.2 How do I handle (carry) a QCL?

The most delicate parts of a QCL are the laser chip itself and the bonds connecting it to the ceramic pads. Therefore the QCL should be touched only at the copper carrier (far from the laser chip and the bonds), or at the ceramic pads (again away from the bonds).

To insert it into or to take it out of the starter-kit housing, gently grab the ceramic pad from above with fine tweezers, and whenever possible, carry the QCL placed flat on a stable surface. Take special care not to touch bonds nor the laser chip itself, since this can immediately destroy the QCL.

Avoid contact of the front facet of the QCL with any object (like the walls of a box where it is stored).

2 Electrical and optical properties

This chapter discusses electrical properties of pulsed and CW QC lasers; for special issues concerning CW operation, see Chapter 4 [CW mode], page 10.

2.1 Electrical limits

2.1.1 What is the maximum allowed duty cycle?

This strongly depends on the laser.

As a general rule, most lasers sold by Alpes Lasers SA are capable of being driven up to 10% duty cycle with pulse lengths up to 100ns. Whenever you drive a laser at a duty cycle higher than specified, monitor the average output power; do not increase the duty cycle any more when the power saturates, but reduce it again to stay on the safe side.

If possible, increase the duty cycle by reducing the pulse period, not by increasing the pulse length, since the latter is more dangerous: It increases the short time heat load on the laser, instead of the average heat load.

Before doing such experiments, it is recommended to contact Alpes Lasers SA, otherwise the responsibility is with you.

2.1.2 What happens if I increase the duty cycle?

You will see no decrease of the maximum instantaneous power of the device up to 2..5% depending on the device. Around 5..20%, the maximum average power will be obtained. Over this limit, the increase of average power due to increase of duty cycle will be smaller than its decrease due to increased threshold current (caused by higher average temperature of the structure).

The precise percentages depend both on the technology used (normal pulsed 2 mW or high power DFB) and the wavelength. For normal pulsed devices at short wavelength (4..5um), the maximum duty cycle is 3..5%, and at longer wavelength it may go up to 8% or even 20% for high power DFBs.

2.1.3 What is the lifetime of the laser (MTBF)?

At present only extrapolated lifetime experiments have been performed and they show more than 10 years extrapolated lifetime at 20C. The measurements have been done operating devices under N2 atmosphere at 130C in pulsed mode at 130% of threshold current. (An activation energy of 0.7 eV has been used to convert the high temperature life time of 350 to 500 hours to room temperature life time.)

2.2 Electrical properties

For information about thermal properties, See Section 3.1 [Heating and Cooling], page 7.

2.2.1 What impedance does a QCL show?

The impedance of a QCL depends strongly on the wavelength it is designed for, the temperature and the mode it is operated, therefore only rough indications can be given here (consult the datasheet of a particular laser for exact behaviour).

Pulsed mode devices have an impedance in the region of 5..50ohm up to about half the threshold current, then it decreases to the region of 0.5..5ohm. When operated at too high current, the impedance can rise again (a condition to be avoided in any case).

2.2.2 Can I check the impedance with an ohm-meter?

Certainly (as long as the applied current is not higher than 10mA), but it might not give you a lot of information, since the impedance varies strongly with the temperature of the QCL, and normal ohm-meters do not specify the applied current. Therefore, the measured impedance varies also with the resistance range of the ohm-meter, and between different ohm-meters. This is also the reason why Alpes Lasers SA does not specify the DC resistance of QCLs.

2.2.3 Where is the cathode of a QCL?

Generally, the cathode is connected to the ceramic pads and the anode is connected to the copper carrier. It may happen that the laser is mounted junction down; this case is clearly indicated on the laser box, and then the cathode is connected to the carrier and the anode to the bonding pads.

2.2.4 How do I drive a pulsed QCL? Can I use a standard laser driver?

Unfortunately, it is in general not possible to use a standard laser driver for a QCL, as in most cases the compliance voltage, current and rise/fall time are not compatible.

Requirements for a pulsed QCL:

- pulse current of up to 10A
- voltage of up to 12V
- maximum rise/fall time of 10ns (to prevent detrimental heating)

Alpes Lasers SA produces starter-kits which provide at the same time driving, temperature control and protection of the laser chip. See Chapter 3 [Starter kit], page 7. For a CW QCL, some standard laser drivers can provide the necessary conditions.

2.2.5 How do I drive a CW QCL?

A CW QCL is about as sensitive to electrical surges and instabilities as a conventional bipolar laser diode (telecom NIR laser). It is necessary to use a good quality power supply to ensure:

- current onset is formed by well controlled ramps without surges;
- current and voltage compliance can be precisely set (1mV/1mA);
- current and voltage are stable within 0.1%.

We recommend source-meters like Keithley 2400 (if possible with 3A option). It seems that Laser Components provides a controller which can be adapted for QCLs provided the voltage compliance is increased.

2.3 Optical properties

2.3.1 Mode characteristics

The emitted mode is single lateral, and also single longitudinal for the DFB devices. The divergence is 60deg FWHM in the vertical direction and 10 to 20deg FWHM in the horizontal direction (see the images on our website at http://www.alpeslasers.ch/technology/Technology.htm).

2.3.1.1 Why do we observe such a far field?

The QCL is based on a mechanism (inter sub-band transitions) that exhibits a poor efficiency: most of the electrons emit phonons instead of photons. The laser thus heats a lot and thermal management at the microscopic scale of the waveguide is important to allow operation. The waveguide is thus very small in the vertical direction (i.e. perpendicular to the quantum wells plane) in order to optimize the overlap between the optical mode and the gain region.

2.3.1.2 Why is the horizontal divergence not the same for all lasers?

Depending on the wavelength and parameter optimised in a laser, it requires a different optimization of the width of the laser stripe. This results in a varying lateral confinement on the beam, thus various lasers at different wavelengths may exhibit pretty different lateral divergence. The lateral divergence is always smaller than the vertical divergence.

2.3.1.3 Is it possible to reduce the divergence?

The divergence in the vertical direction is a parameter that is governed by the thickness of the laser waveguide. It is high because the waveguide is narrow. Reducing the divergence would impair the performances of the laser. Moreover this modification would need tremendous development effort and it would be necessary to compromise on the power and operation temperature.

2.3.2 What is the polarisation of the emitted mode?

The polarisation is vertical and very pure as there is a quantum mechanical selection rule forbidding emission in the horizontal direction.

2.3.3 How do I collimate the beam?

Due to the large divergence of the beam, it is recommended to use fast optics (f/1 ... f/0.8) to collect most of the emitted light. We recommend aspheres from Janos (see http://www.janostech.com).

2.3.4 How do I calculate the brilliance?

The brilliance can be estimated in two ways:

- Supposing the laser is emitting monomode transversal and ideal optics for a gaussian 00-beam apply, the brilliance is then given by $B = 4 \times P/(\lambda^2)$, with P the optical output power and λ the wavelength of the laser.
- Using standard values (which can vary for up to factors of 2 between lasers), the aperture A is in the range of 0.03mm by 0.005mm, and the illuminated solid angle (for 60deg vertical and 20deg horizontal divergence) W is in the range of 0.3 (or $2 \times \pi \times 0.045$), and therefore the brilliance $B = P/A/W$ or approximately B=P/(4e-5mm^2).

These are highly approximative values; if you need well defined ones, ask for the needed values for a specific laser you are interested in.

3 Starter kit (pulser, temperature controller etc)

This chapter discusses properties of the Starter kit, used for pulsed mode lasers.

3.1 Operation of TE cooler

3.1.1 What is the dissipated heat of a pulsed QC laser?

Pulsed QC lasers in general work at threshold voltages of 9V...12V and threshold currents of 1A...3A, with maximum values of up to 13V and 10A. The peak power during operation therefore can vary in the range of about 10W...130W. Depending on duty cycle, the mean dissipated power normally is in the range of some Watts.

3.1.2 What temperatures can be reached with the TC-51?

Normally, the TC-51 is shipped with current limitation of 4.5A and alarm value of 65degC. Depending on the heat sink used, temperatures between -35 and +60degC may be reached. Very high and low temperatures induce more stress on the Peltier elements and therefore accelerate ageing.

3.2 Important points concerning LDD pulsers

3.2.1 What are the possible pulse lengths and duty cycles?

The pulse driver LDD100 can amplify pulses with lengths of 5ns...300ns and minimal period of 100ns. Maximal duty cycle is 50% (with reduced stability and not continuously to prevent overheating, up to 90%). The pulse generator TPG128 is capable of generating pulses with lengths of 20ns...200ns (with reduced stability down to 10ns) and period of 0.2us...10.5us. Duty cycle can vary in the range of 0.1%...80% (with reduced stability up to 95%).

In combination with LDD100, only 50% duty cycle can be reached, since the power supply in TPG128 which is feeding LDD100 is not specified for higher values. Provide external power source for LDD100 if more than 50% is needed. In any case, contact Alpes Lasers SA first, if duty cycles of more than 5% are needed.

3.2.2 What is the "external power supply" used for?

The "external power supply" is a DC power supply provided by the user; it is connected (via banana plugs) to the pulse driver LDD100 and is delivering the electrical power feeding the laser. Any standard laboratory power supply can be used, as long as it is ripple-free (<=1%), voltage regulated, with variable voltage from 0V to at least 35V, and capable of delivering 1A DC for duty cycles up to 5%. For higher duty cycles, contact Alpes Lasers SA, since not all lasers are capable of working at more than 5%.

3.3 Low-frequency bias current for modulation

This section describes use of a bias-T circuit for electrically controlled modulation of peak emission wavelength.

3.3.1 What are function and purpose of a bias-T circuit?

3.3.1.1 What is the function of the bias-T?

The bias-T allows to apply a constant (DC) current to the laser in addition to the pulsed current (therefore a bias-T is useless in CW mode). The current is drawn from the external (user supplied) power supply through the laser.

This current can be controlled electrically. Alpes Lasers SA specifies use up to of 0.1kHz, but several clients have used the bias-T successfully at frequencies of up to several kHz.

3.3.1.2 What is the purpose of using a bias-T?

Since tuning of a QC laser is done by changing the temperature of the active zone, the DC bias current can be used to control the emission wavelength of the laser via its heating effect. The bias-T therefore allows for electrically controlled rapid scanning of the emission wavelength.

3.3.1.3 Why is using a bias-T better than changing base temperature?

Tuning can also be achieved by changing the temperature of the whole laser but at much lower speed, due to the high thermal capacity of the laser submount and laser base. Heating of the active zone alone by applying a DC bias current is affecting only the active zone and the surrounding parts of the laser chip, and due to the small thermal capacity of this tiny volume, the laser emission responds much faster to DC bias current variations.

3.3.2 What are the connections of the bias-T circuit?

The bias-T circuit is either separately attached to the low-impedance line connecting the pulser and the laser housing, or directly included in the pulser. Connections are different in the two cases:

External circuit connected to low-impedance line
: In this case, the bias-T box is soldered to the top contact of the low-impedance line with the red wire. The black wire (with banana plug) must be connected to the negative pole of the external user supply. The connector labelled IN receives the control voltage (0.6. . .2.6V, center positive), the connector labelled MONI allows monitoring of the bias current.

Circuit included in pulser unit
: The circuit included in the LDD100 pulser unit is controlled by the twisted black and yellow wires of the control cable (with the DSUB-9 plug). They correspond to the shield and center of the IN connector in the former case (positive voltage on yellow wire). This version has no monitor connection.

3.3.3 Dangers and disadvantages of using a bias-T circuit

- Since a bias-T only allows to heat the laser, the emission wavelength can only be increased (or emission wavenumber decreased), and output power will decrease with increased bias current, due to the additional heating. This means that the laser should be operated initially at lowest possible temperature, and it reduces the number of lasers available for reaching a given emission wavelength.

- Heating of the active zone will increase thermal stress of the laser, therefore the expected lifetime will decrease more rapidly compared to increasing the temperature of the laser submount and base in total. If operation at only a fixed wavelength is needed, this should be adjusted with the overall temperature control.
- Too high a DC bias current can immediately destroy the laser due to catastrophic thermal roll-over. Therefore set-up of the bias current has to be done only by instructed personnel, and after checking with Alpes Lasers SA for allowed parameter ranges; otherwise warranty will be lost.

3.3.4 What has to be kept in mind before use?

- All use of a bias-T on a specific QC laser has to be accepted by Alpes Lasers SA before; otherwise all warranty will be lost.
- The bias-T should never be used at the highest specified current or output power, otherwise the risk of thermal roll-over failure is imminent.
- If optical output power can be monitored, this should be used during set-up of the bias-T to make sure that thermal roll-over is not reached: Temporary increasing of the pulse current must always result in increased optical power output, otherwise the DC bias current is already too high.
- As a rule of thumb, the overall dissipated power (sum of DC bias current dissipation and pulse current dissipation) must never be higher than the average dissipated power given by the highest current / voltage / temperature combination specified in the datasheet. Take into account that the average dissipated power for a given pulse current I, pulse voltage U, and duty cycle d is given by $d \times I \times U$, whereas the dissipated power due to a bias current IB is given by $IB \times U$. (U is the voltage on the laser, but it is safe for this calculation of bias current dissipation to use the voltage on the LDD pulser input.)

3.3.5 What are the current and voltage ranges of the bias-T circuit?

Since the input stage of the bias-T is a bipolar transistor, applied voltage must be higher than about 0.6V to start bias current. The input stage has maximum voltage limit of 2.6V, but the laser itself may be destroyed at lower bias-T control voltage already, therefore the maximum rating has to be checked with the abovementioned rules and together with Alpes Lasers SA.

The monitor output (if available) allows measurement of applied DC bias current: Its voltage divided by 10ohm gives bias current. In general, bias current can be in the range of 0.1A, but this must be checked with Alpes Lasers SA before.

Avoid reverse polarity on the input!

4 Operating QCLs in continuous wave mode

For electrical properties, see Section 2.2 [Electrical properties], page 3.

4.1 Thermal properties

The dissipated heat of a QC laser operated in CW mode is in the range of some Watts (operating voltage in the 8V. . . 12V range, current in the 0.5A. . . 1.5A range). Keep in mind that in general, the impedance of a QCL is decreasing with temperature!

4.2 Availability of CW lasers

CW QCLs are now commercially available for operation at cryogenic (LN2) temperatures (single- and multi-mode devices). Availability of CW FP devices for operation at room temperature is expected during 2004; currently no date for commercial availability of CW single-mode devices at room temperature can be given.

State of the art in research is that experimental multimode devices have been shown working, as well as DFB devices; however, better control of manufacturing is needed to make them available as commercial products.

5 General QCL questions

This chapter discusses some general properties of QC lasers, mainly concerning optical behavour. For additional information, See Chapter 2 [Electro-optical], page 3.

5.1 available QC laser series

Alpes Lasers SA provides three types of single mode devices:

RT-P-DFB-2-X
: designed for chemical sensing of atmospheric pressure gases in a room temperature (Peltier cooled) system. These devices are available from 4 to 17 um built to order, and also off the shelf devices are available. Please check http://www.alpeslasers.ch/lasers-on-stock/lasersSTAN.html for an online list of such lasers on stock!

  The optical output is guaranteed to be larger than 2 mW average with a lower than 0.4/cm linewidth. The effective linewidth is smaller but not guaranteed as the standard resolution of our characterisation setup is 0.3/cm. For an example of application, please consult the paper by M. Zahniser (Aerodyne) on our web site under http://www.alpeslasers.ch/Conference-Papers/Workshop-Freiburg-01.pdf.

RT-HP-DFB-[5,10,20]-X
: designed for chemical sensing of atmospheric pressure gases in a room temperature (Peltier cooled) system with a low sensitivity detector or a photoacoustic setup. The parameters are the same as for the RT-P-DFB-2-X series except that the power can be up to 5, 10, 20 mW average. Please note that for certain regions of the spectrum, the availability of the devices is not guaranteed. Please inquire!

LN2-CW-DFB-[1,2,5,10]-X
: designed for extremely fine spectroscopy of narrow lines. The available powers are 1, 2, 5, 10 mW (some devices up to 100mW), the laser operates CW at LN2 temperature, it thus requires a DC power supply and a LN2 dewar. The linewidth guaranteed is smaller than 0.3/cm due to the same limitation as for the RT-P-DFB-2-X, but measurements performed on a Fabry-Perot etalon of a typical device showed a narrower than 4 MHz linewidth (unpublished), and beating between a CO2 laser and a typical device showed linewidth narrower than 8 MHz (to be published by D. Courtois, CNRS Reims).

The RT-CW-DFB-1-X serie is being developed as a replacement for the LN2-CW-DFB-1-X series for the same range of applications but without the LN2 Dewar. This product is expected to be commercially available in 2004.

Multimode operation

For such devices output power can be up to several times higher than that of single mode devices. Please ask, since devices of that quality may often be available from stock, even without being published on stock lists.

5.2 How to measure QC laser emission?

At Alpes Lasers SA, the following methods are used for detection and qualification of QC laser emission:

Power meter
: To measure power, semiconductor power meters are used, in particular the combination of power head 2A-SH with meter AN/2 from OPHIR (http://www.ophiropt.com).

Spectrometer
: Standard measurements are done with TRIAX320 monochromators from Jobin Yvon (http://www.jobinyvon.com), special (high resolution and CW) measurements with Nicolet 800 and 860 FTIR (http://www.nicolet.com).

fast detectors
: For time-critical measurements, Alpes Lasers SA recommends detectors from VIGO SYSTEMS (http://www.vigo.com.pl).

monitoring
: For monitoring laser emission, simple pyroelectric detectors can be used, e.g LGTP101 by MemTek (http://memtek.lgcit.com).

5.3 General emission characteristics

5.3.1 What wavelengths can be reached?

QC devices have been shown to be capable of operating between 3.44 and 84um. Devices with wavelength ranging from 5 to 11 um are actually available. Nevertheless we encourage you to discuss your needs if they lay outside this range.

5.3.2 Why is such a large range obtainable?

This peculiar characteristic is due to the fact that in QC devices the emission wavelength is determined by the geometry of the semiconductor layers that compose the laser crystal.[1] More precisely, the laser transition is the transition of an electron inside sub-bands from one upper quantum well level to a lower quantum well level. For more details we would encourage the reader to consult semiconductor physics text book.

Using two different semiconductor materials (InGaAs and AlInAs), a series of potential wells and barriers for the electrons can be built. These wells and barriers are so thin that the electrons are allowed only a discrete set of energy levels. This situation is very similar to the orbitals of an electron around a nucleus in the case of an atom. In the case of the QC structure, the positions of the permitted energy levels are determined by the thicknesses of the wells and barriers.

It is thus possible, using only one material system (InGaAs/AlInAs grown on InP), to define laser transitions with energies ranging over a wide span. The limits are set, on the short wavelength range, by the potential difference between the wells and barriers, and on the other side by intrinsic absorptions of the material.

In conclusion, a QC laser is a laser made with some sort of a specific composit designed specifically for each wavelength but always composed of the very same materials.

5.3.3 How "CW" does a QCL look like in pulsed mode?

For a slow detection system, a pulsed laser will appear CW. In order to define slow, See Section 5.4.3 [Line-width limit], page 13. A pulse will last between 10 and 100 ns and will be

[1] In standard bipolar semiconductor lasers (e.g. 1.55um telecom devices), the emission wavelength is closely related to an intrinsic characteristic of the semiconductor material used, namely the band gap energy.

repeated at a rate corresponding to 0...3% for usual DFBs and up to 10...20% for high power DFBs. At 10 ns pulse length, the line-width will be close to minimal in pulsed operation, less than 0.1/cm, and at 100 ns it will be larger, depending on the device.

5.3.4 What optical powers can be expected?

See Section 5.1 [QCL series], page 11.

5.3.5 How precise should emission be specified?

Normally, specification to 0.5/cm or 1nm should be sufficient. As the laser tunes over several linewidths, it is possible to temperature tune it to adjust its central wavelength. It becomes critical only if extreme power is required or if the laser has to operate CW at LN2 for the same reason.

5.4 Tuning and linewidth

5.4.1 How does a DFB-QCL tune?

In QCLs there are no effects such as carrier density dependent index of refraction, therefore no current tuning is observed. The only tuning mechanism is temperature tuning of the index of refraction of the waveguide that changes the apparent optical length of the wavelength selection grating. This of course will result in an observable current tuning: the higher the current gets, the higher becomes the average temperature of the active region of the QCL. But this apparent current tuning is based on temperature tuning only.

5.4.2 How much can a DFB-QCL be tuned?

The operation range of the device is -30...+30degC (dT=60K). The relative tuning is constant for all wavelengths and is about 6E-5/K for wavelength and -6E-5/K for wavenumber. This results in a tuning range of about 0.4% of peak emission wavelength or wavenumber.

For a 1500/cm device, the total tuning is approximately given by $-6E-5/K \times 60K \times 1500/cm$ i.e -5.4/cm.

Note: The relative tuning has a minus sign for wavenumbers and a positive sign for wavelength. This is exactly opposite to how a lead-salt device would tune, for those accustomed to this type of devices.

5.4.3 Why is the line-width of a DFB-QCL limited?

Like in every pulsed lasers, short enough pulses will lead to Fourier limited line width. For intermediate pulse length, the limiting factor is the thermal tuning of the device. The device heats up during the pulse and its emission wavelength follows and sweeps. Optimum pulses of 5 to 15 ns will enable to get a minimal linewidth.

Some customers such as the company Aerodyne published data on the linewidth reachable using our devices and electronics (starter-kit). Please have a look at http://www.alpeslasers.ch/Conference-Papers/Workshop-Freiburg-01.pdf which describes measured line width in pulsed operation.

The standard measurement setup we use enables to verify that the laser is single mode i.e. has a linewidth not exceeding 0.3/cm.

5.4.4 How and how much does a FP-QCL tune?

A FP-QCL tunes because of the shift in gain of the structure with temperature. This tuning is about twice as fast as the index tuning of DFB-QCLs, i.e about 1.3E-4/K (increasing temperature will result in increased wavelength).

On a Peltier cooler like the one included in the Alpes Lasers SA starter-kit, the obtainable temperature span is about 60K (-30. . .+30degC). Therefore the central wavelength can be shifted by about 1.3E-4/K*60K or approximately 0.8% from the lowest to the highest temperature.

6 Commercial matters

6.1 Laser and starter-kit delivery times

Off-stock devices can be obtained within less than two weeks. For built-to-order devices, we offer 6 months lead time, due to the delicate nature of the fabrication process. This time can be reduced in case the needed wavelength requires only reprocessing of an existing laser crystal, and not redesign of a new one.

Electronic equipment normally has delivery times of two to three weeks.

7 Glossary and Abbreviations

CW Continuous Wave; for lasers this means operation with DC current, generating uninterrupted emission. See Chapter 4 [CW mode], page 10.

DFB Distributed Feed-Back; describing a laser with an etched grating close to its active zone, which acts as a filter, reducing overall gain for all but the wavelengths defined by the grating period. This technique allows to produce single-mode lasers also for pulsed mode operation.

FP Fabry-Pérot; describing a laser whose emission spectrum is only defined by the gain of the active zone and the cavity of the cleaved laser chip, in contrast to a DFB laser.

FTIR Fourier-Transform InfraRed; describing a type of spectrometer, See Section 5.2 [Detection], page 11.

LN2 Liquid Nitrogen. Used also to describe temperature ranges reachable in LN2-cooled systems with Dewars (approximatively 80...130K).

MTBF Mean Time Between Failure. See Section 2.1.3 [Lifetime], page 3.

QCL Quantum Cascade Laser.

RT Room Temperature. In a more general way meaning temperatures in the range of -30...+50degC, in contrast to cryogenic temperatures.

TE Thermo-Electrical: TE coolers use Peltier elements as semiconductor heat pump.

Alpes Lasers

Alpes lasers is the first company offering the emerging Quantum Cascade Laser technology for spectroscopy application.

Products

RT-P-FP-2...50-X

Lasers designed for acqueous chemical sensing.
- Room temp. operation
- Pulsed
- Multiple line emission
- Single lateral mode
- Far field 10°x60° FWHM
- 2,5,10,20,50 mW average power
- Wavelength off stock: 4.6, 5.2, 6, 10.35, 17µm and many others, please ask (not all power rating are available).
- Built to order from 3.5 to 17 µm

RT-CW-FP-5-X

Lasers specifically designed for Free Space Optics (FSO) data transmission.
- Room temp. operation
- CW operation
- Multiple line emission
- Single lateral mode
- Far field 10°x60° FWHM
- 5 mW average power
- Wavelength off stock: 9.3 µm.
- Available 2003

RT-CW-DFB-1-X

Lasers specifically designed for high resolution chemical sensing.
- Room temp. operation
- CW operation
- Single line emission
- Single lateral mode
- Far field 10°x60° FWHM
- 1 mW average power
- Available 2003

Alpes Lasers

CP 58
CH-2008, Neuchâtel
Switzerland

Tel +41 878 803 041
Fax +41 878 803 042

www.alpeslasers.ch
info@alpeslasers.ch

Getting started

Q: How do I operate a QCL?

A: A **starter kit** is proposed in order to obtain a fully functional, stand alone Quantum Cascade Laser light source with no additional effort at competitive prices. Alpes Lasers provides all the necessary parameters and instructions to operate at best the lasers in its **Starter Kits**. Once unpacked, the laser with the **Starter Kit** operates within minuts.

Q: How do I integrate a QCL in a system?

A: A OEM version of the **Starter Kit** is available at a reduced price compared to the stand alone version. A multiple temperature controler unit (2, 4, 6 units) is available for 19"rack mount. A miniature pulser integrated in the laser box will be available end 2002.

Q: How do I get support operating a QCL?

A: A Alpes Lasers' Quantum Cascade Laser specialist can assist you starting the laser and get the most out of it. Alpes Lasers personnel totalises now more than 20 years of experience in the field of Quantum Cascade Lasers and this knowledge is available to our customers directly on the phone.

Q: Can I obtain a QCL at a specific wavelength?

A: Any wavelength can be obtained in from 3.5 to 17 µm a Alpes Lasers specialist will assist you specifying the laser you need. It takes then from four to six month to built the ordered device.

Alpes Lasers

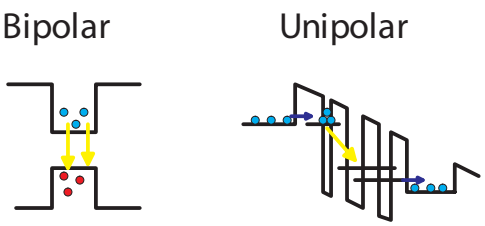
Alpes lasers is the first company offering the emerging Quantum Cascade Laser technology for spectroscopy application.

The Quantum Cascade Laser

The Quantum Cascade Laser (QCL) is a semiconductor laser involving only one type of carrier and which is based on two fundamental phenomena of quantum mechanics, namely tunnelling and quantum confinement.
In an intersubband laser, there is no electron-hole recombination. In a QCL, electrons are making transitions between bound states created by quantum confinement in ultra-thin alternating layers of semiconductor materials. Since these ultra-thin layers, called quantum wells, have a size comparable to the electron's de Broglie wavelength, they restrict the electron motion perpendicular to the plane of the layer. Because of this effect called quantum confinement, the electron can only jump from one state to the other by discrete steps, emitting photons of light. The spacing between the steps depends on the width of the well, and increases as the well size is decreased. Using the same base semiconductors (InGaAs and AlInAs grown on InP) allows the manufacture of lasers with emission wavelength from 3.5 to 12 μm.
Compared to conventional (inter-band) lasers, the QCL has the following advantages:
- This semiconductor material can be used to manufacture lasers operating across the whole mid-infrared.
- QCL technology is intrinsically more robust (no interface recombination).
- Since the dominant non-radiative recombination mechanism is optical phonon emission and not Auger effect (e.g narrow-gap materials), it allows intrinsically higher operating temperature. Today QCL is the only semiconductor laser operating at and above room temperature (typ. up to 40C) .

J. Faist, F. Capasso, D. L. Sivco, C. Sirtori, A. L. Hutchinson, and A. Y. Cho "Quantum Cascade Laser", Science, 264, 553, (1994);
J. Faist, F. Capasso "Quantum Cascade Laser" Mc Graw-Hill Yearbook of Science and Technology 1997, p265-267

Alpes Lasers
CP 58
CH-2008, Neuchâtel
Switzerland
Tel +41 878 803 041
Fax +41 878 803 042
www.alpeslasers.ch
info@alpeslasers.ch



Products

RT-P-DFB-2-X

Lasers specifically designed for chemical sensing.
- Room temp. operation
- Pulsed
- Single line emission
- Single lateral mode
- Far field 10°x60° FWHM
- 2 mW average power
- Wavelength off stock: 4.6, 5.2, 10.35, 17μm and many others, please ask.
- Built to order from 3.5 to 17 μm

RT-HP-DFB-5,10,20-X

Lasers specifically designed for photoacoustic measurements.
- Room temp. operation
- Pulsed
- Single line emission
- Single lateral mode
- Far field 10°x60° FWHM
- 5,10,20 mW average power
- Wavelength off stock: 10.35 μm.
- Built to order from 5 to 12 μm